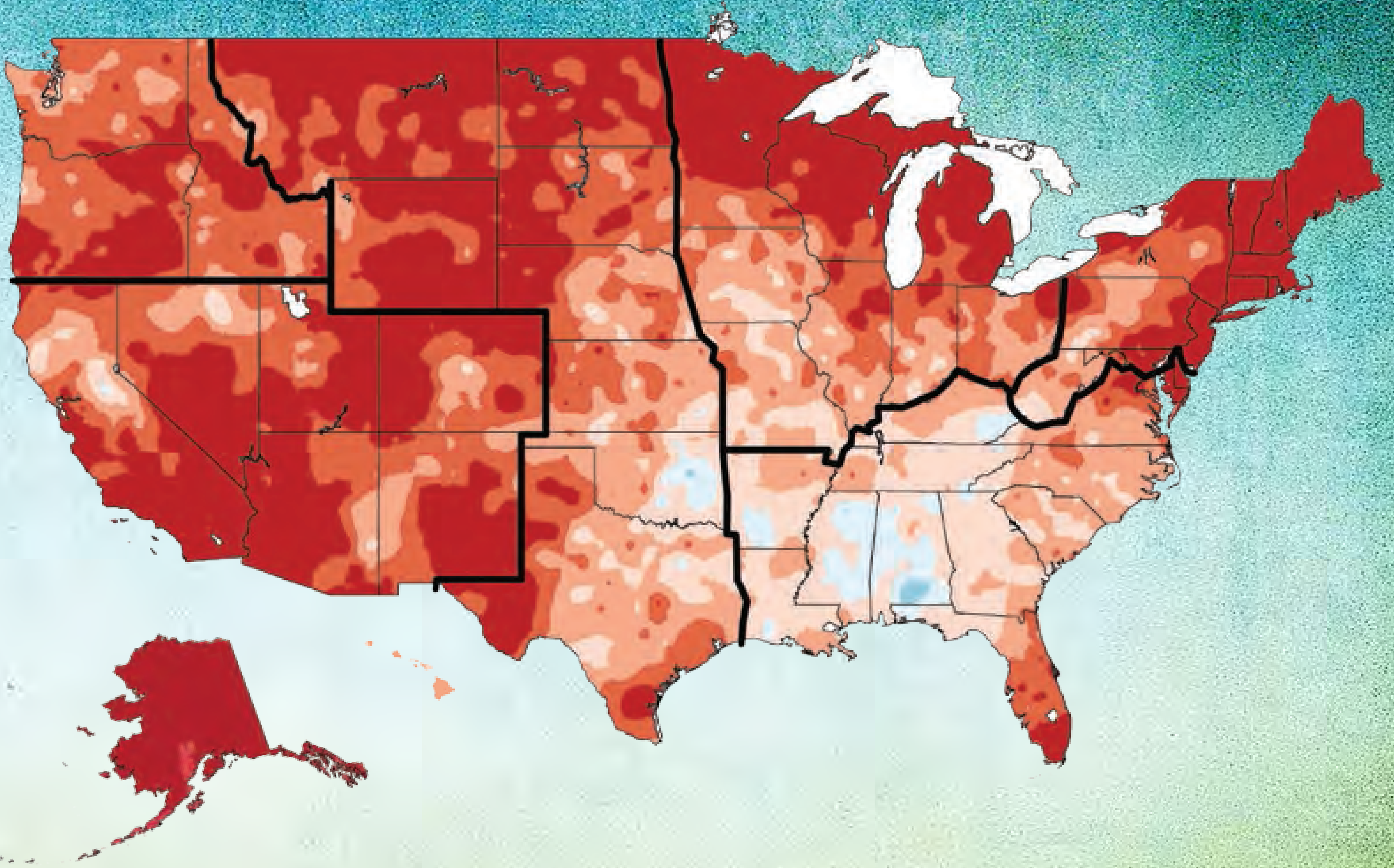
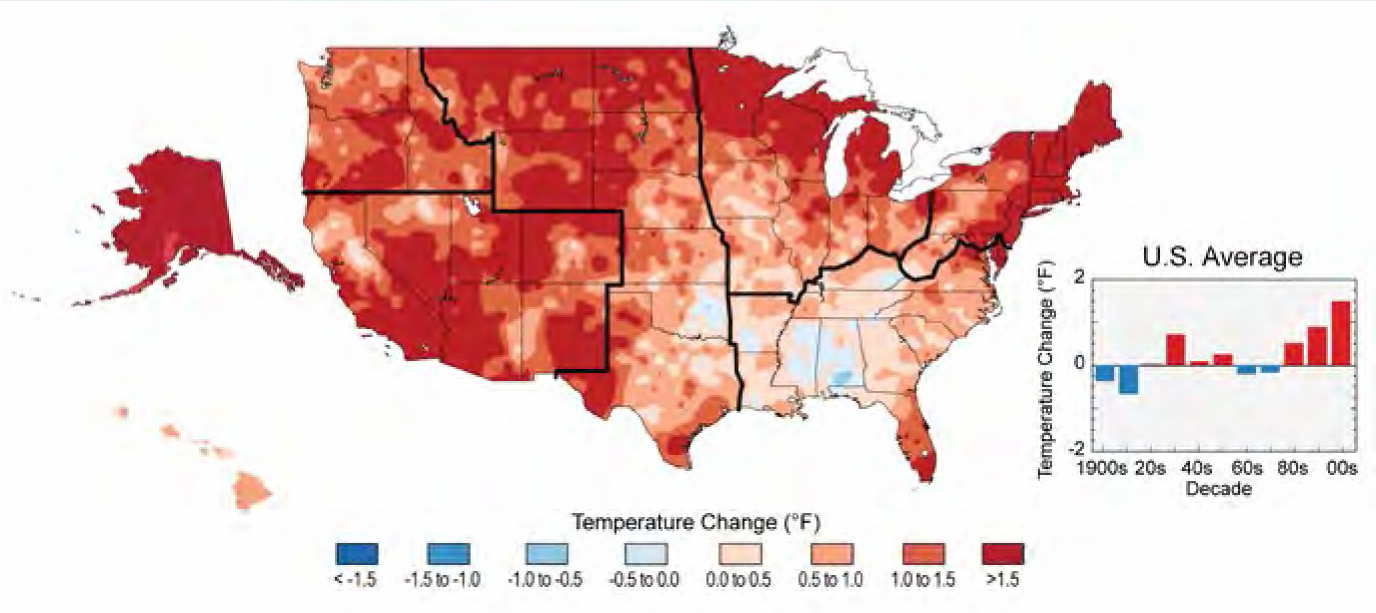
Climate Change Impacts in the United States



U.S. National Climate Assessment
U.S. Global Change Research Program

Climate Change Impacts in the United States

Observed U.S. Temperature Change



The colors on the map show temperature changes over the past 22 years (1991-2012) compared to the 1901-1960 average for the contiguous U.S., and to the 1951-1980 average for Alaska and Hawaii. The bars on the graph show the average temperature changes for the U.S. by decade for 1901-2012 (relative to the 1901-1960 average). The far right bar (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 was warmer than any previous decade in every region. (Figure source: NOAA NCDC / CICS-NC).

DoD photo by Staff Sgt. Michael Crane, U.S. Air Force

Members of the National Guard lay sandbags to protect against Missouri River flooding.

©Jim West/imagebroker/Corbis

Energy choices will affect the amount of future climate change.

AP Photo/The Press-Enterprise/Terry Pierson

Climate change is contributing to an increase in wildfires across the U.S. West.

©Dennis Schroeder, NREL

Solar power use is increasing and is part of the solution to climate change.

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May 2014

Members of Congress:

On behalf of the National Science and Technology Council and the U.S. Global Change Research Program, we are pleased to transmit the report of the Third National Climate Assessment: *Climate Change Impacts in the United States*. As required by the Global Change Research Act of 1990, this report has collected, evaluated, and integrated observations and research on climate change in the United States. It focuses both on changes that are happening now and further changes that we can expect to see throughout this century.

This report is the result of a three-year analytical effort by a team of over 300 experts, overseen by a broadly constituted Federal Advisory Committee of 60 members. It was developed from information and analyses gathered in over 70 workshops and listening sessions held across the country. It was subjected to extensive review by the public and by scientific experts in and out of government, including a special panel of the National Research Council of the National Academy of Sciences. This process of unprecedented rigor and transparency was undertaken so that the findings of the National Climate Assessment would rest on the firmest possible base of expert judgment.

We gratefully acknowledge the authors, reviewers, and staff who have helped prepare this Third National Climate Assessment. Their work in assessing the rapid advances in our knowledge of climate science over the past several years has been outstanding. Their findings and key messages not only describe the current state of that science but also the current and future impacts of climate change on major U.S. regions and key sectors of the U.S. economy. This information establishes a strong base that government at all levels of U.S. society can use in responding to the twin challenges of changing our policies to mitigate further climate change and preparing for the consequences of the climate changes that can no longer be avoided. It is also an important scientific resource to empower communities, businesses, citizens, and decision makers with information they need to prepare for and build resilience to the impacts of climate change.

When President Obama launched his Climate Action Plan last year, he made clear that the essential information contained in this report would be used by the Executive Branch to underpin future policies and decisions to better understand and manage the risks of climate change. We strongly and respectfully urge others to do the same.

Sincerely,

John P. Holdren

Dr. John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy
Executive Office of the President

Dr. Kathryn D. Sullivan
Under Secretary for Oceans and Atmosphere
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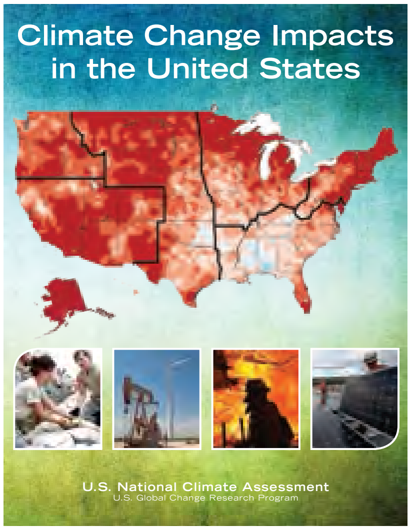
About the NATIONAL CLIMATE ASSESSMENT

The National Climate Assessment assesses the science of climate change and its impacts across the United States, now and throughout this century. It documents climate change related impacts and responses for various sectors and regions, with the goal of better informing public and private decision-making at all levels.

A team of more than 300 experts (see page 98), guided by a 60-member National Climate Assessment and Development Advisory Committee (listed on page vi) produced the full report – the largest and most diverse team to produce a U.S. climate assessment. Stakeholders involved in the development of the assessment included decision-makers from the public and private sectors, resource and environmental managers, researchers, representatives from businesses and non-governmental organizations, and the general public. More than 70 workshops and listening sessions were held, and thousands of public and expert comments on the draft report provided additional input to the process.

The assessment draws from a large body of scientific peer-reviewed research, technical input reports, and other publicly available sources; all sources meet the standards of the Information Quality Act. The report was extensively reviewed by the public and experts, including a panel of the National Academy of Sciences, the 13 Federal agencies of the U.S. Global Change Research Program, and the Federal Committee on Environment, Natural Resources, and Sustainability.



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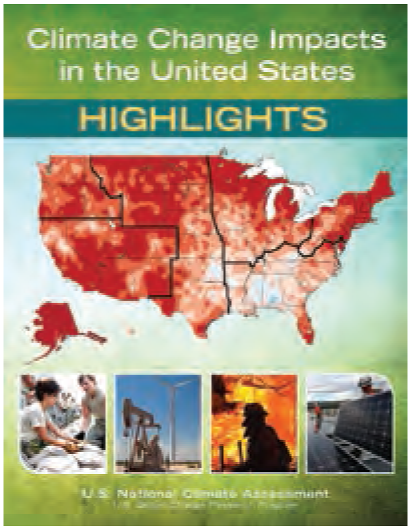
About the HIGHLIGHTS

The *Highlights* presents the major findings and selected highlights from *Climate Change Impacts in the United States*, the third National Climate Assessment.

The *Highlights* report is organized around the National Climate Assessment's 12 Report Findings, which take an overarching view of the entire report and its 30 chapters. All material in the *Highlights* report is drawn from the full report. The Key Messages from each of the 30 report chapters appear in boxes throughout this document.

A 20-page *Overview* booklet is available online.



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CONTENTS

SECTORS 68

REGIONS..................................369

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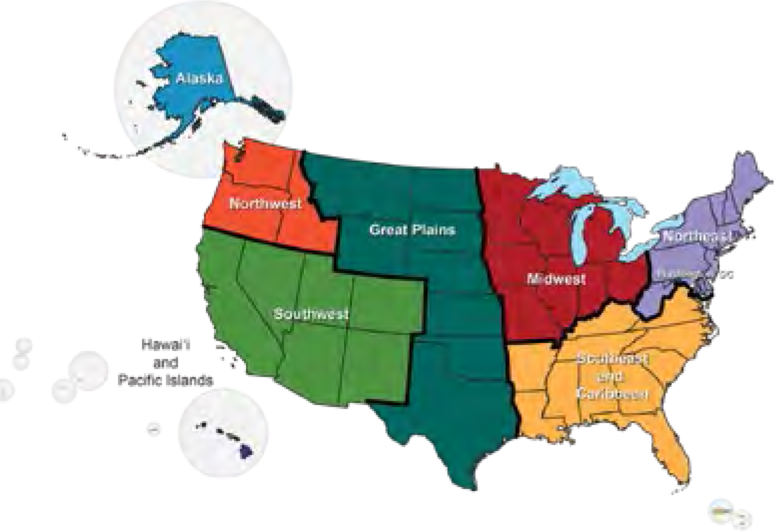
RESPONSE STRATEGIES........................619

APPENDICIES



CLIMATE CHANGE AND THE AMERICAN PEOPLE

Climate change, once considered an issue for a distant future, has moved firmly into the present. Corn producers in Iowa, oyster growers in Washington State, and maple syrup producers in Vermont are all observing climate-related changes that are outside of recent experience. So, too, are coastal planners in Florida, water managers in the arid Southwest, city dwellers from Phoenix to New York, and Native Peoples on tribal lands from Louisiana to Alaska. This National Climate Assessment concludes that the evidence of human-induced climate change continues to strengthen and that impacts are increasing across the country.

Americans are noticing changes all around them. Summers are longer and hotter, and extended periods of unusual heat last longer than any living American has ever experienced. Winters are generally shorter and warmer. Rain comes in heavier downpours. People are seeing changes in the length and severity of seasonal allergies, the plant varieties that thrive in their gardens, and the kinds of birds they see in any particular month in their neighborhoods.

Other changes are even more dramatic. Residents of some coastal cities see their streets flood more regularly during storms and high tides. Inland cities near large rivers also experience more flooding, especially in the Midwest and Northeast. Insurance rates are rising in some vulnerable locations, and insurance is no longer available in others. Hotter and drier weather and earlier snowmelt mean that wildfires in the West start earlier in the spring, last later into the fall, and burn more acreage. In Arctic Alaska, the summer sea ice that once protected the coasts has receded, and autumn storms now cause more erosion, threatening many communities with relocation.

Scientists who study climate change confirm that these observations are consistent with significant changes in Earth's climatic trends. Long-term, independent records from weather stations, satellites, ocean buoys, tide gauges, and many other data sources all confirm that our nation, like the rest of the world, is warming. Precipitation patterns are changing, sea level is rising, the oceans are becoming more acidic, and the frequency and intensity of some extreme weather events are increasing. Many lines of independent evidence demonstrate that the rapid warming of the past half-century is due primarily to human activities.

The observed warming and other climatic changes are triggering wide-ranging impacts in every region of our country and throughout our economy. Some of these changes can be beneficial over the short run, such as a longer growing season in some regions and a longer shipping season on the Great Lakes. But many more are detrimental, largely because our society and its infrastructure were designed for the climate that we have had, not the rapidly changing climate we now have and can expect in the future. In addition, climate change does not occur in isolation. Rather, it is superimposed on other stresses, which combine to create new challenges.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This National Climate Assessment collects, integrates, and assesses observations and research from around the country, helping us to see what is actually happening and understand what it means for our lives, our livelihoods, and our future. This report includes analyses of impacts on seven sectors – human health, water, energy, transportation, agriculture, forests, and ecosystems – and the interactions among sectors at the national level. This report also assesses key impacts on all U.S. regions: Northeast, Southeast and Caribbean, Midwest, Great Plains, Southwest, Northwest, Alaska, Hawai'i and the Pacific Islands, as well as the country's coastal areas, oceans, and marine resources.

Over recent decades, climate science has advanced significantly. Increased scrutiny has led to increased certainty that we are now seeing impacts associated with human-induced climate change. With each passing year, the accumulating evidence further expands our understanding and extends the record of observed trends in temperature, precipitation, sea level, ice mass, and many other variables recorded by a variety of measuring systems and analyzed by independent research groups from around the world. It is notable that as these data records have grown longer and climate models have become more comprehensive, earlier predictions have largely been confirmed. The only real surprises have been that some changes, such as sea level rise and Arctic sea ice decline, have outpaced earlier projections.

What is new over the last decade is that we know with increasing certainty that climate change is happening now. While scientists continue to refine projections of the future, observations unequivocally show that climate is changing and that the warming of the past 50 years is primarily due to human-induced emissions of heat-trapping gases. These emissions come mainly from burning coal, oil, and gas, with additional contributions from forest clearing and some agricultural practices.

Global climate is projected to continue to change over this century and beyond, but there is still time to act to limit the amount of change and the extent of damaging impacts.

This report documents the changes already observed and those projected for the future. It is important that these findings and response options be shared broadly to inform citizens and communities across our nation. Climate change presents a major challenge for society. This report advances our understanding of that challenge and the need for the American people to prepare for and respond to its far-reaching implications.


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ABOUT THIS REPORT

This report assesses the science of climate change and its impacts across the United States, now and throughout this century. It integrates findings of the U.S. Global Change Research Program (USGCRP)[a] with the results of research and observations from across the U.S. and around the world, including reports from the U.S. National Research Council. This report documents climate change related impacts and responses for various sectors and regions, with the goal of better informing public and private decision-making at all levels.

REPORT REQUIREMENTS, PRODUCTION, AND APPROVAL

The Global Change Research Act[1] requires that, every four years, the USGCRP prepare and submit to the President and Congress an assessment of the effects of global change in the United States. As part of this assessment, more than 70 workshops were held involving a wide range of stakeholders who identified issues and information for inclusion (see Appendix 1: Process). A team of more than 300 experts was involved in writing this report. Authors were appointed by the National Climate Assessment and Development Advisory Committee (NCADAC),[b] the federal advisory committee assembled for the purpose of conducting this assessment. The report was extensively reviewed and revised based on comments from the public and experts, including a panel of the National Academy of Sciences. The report was reviewed and approved by the USGCRP agencies and the federal Committee on Environment, Natural Resources, and Sustainability (CENRS). This report meets all federal requirements associated with the Information Quality Act (see Appendix 2: IQA), including those pertaining to public comment and transparency.

REPORT SOURCES

The report draws from a large body of scientific, peer-reviewed research, as well as a number of other publicly available sources. Author teams carefully reviewed these sources to ensure a reliable assessment of the state of scientific understanding. Each source of information was determined to meet the four parts of the IQA Guidance provided to authors: 1) utility, 2) transparency and traceability, 3) objectivity, and 4) integrity and security (see Appendix 2: IQA). Report authors made use of technical input reports produced by federal agencies and other interested parties in response to a request for information by the NCADAC;[2] other peer-reviewed scientific assessments (including those of the Intergovernmental Panel on Climate Change); the U.S. National Climate Assessment's 2009 report titled Global Climate Change Impacts in the United States;[3] the National Academy of Science's America's Climate Choices reports;[4] a variety of regional climate impact assessments, conference proceedings, and government statistics (such as population census and energy usage); and observational data. Case studies were also provided as illustrations of climate impacts and adaptation programs.

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[a] The USGCRP is made up of 13 Federal departments and agencies that carry out research and support the nation's response to global change The USGCRP is overseen by the Subcommittee on Global Change Research (SGCR) of the National Science and Technology Council's Committee on Environment, Natural Resources and Sustainability (CENRS), which in turn is overseen by the White House Office of Science and Technology Policy (OSTP). The agencies within USGCRP are: the Department of Agriculture, the Department of Commerce (NOAA), the Department of Defense, the Department of Energy, the Department of Health and Human Services, the Department of the Interior, the Department of State, the Department of Transportation, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, the Smithsonian Institution, and the U.S. Agency for International Development.

[b] The NCADAC is a federal advisory committee sponsored by the National Oceanic and Atmospheric Administration under the requirements of the Federal Advisory Committee Act.

A GUIDE TO THE REPORT

The report has eight major sections, outlined below:

- **Overview and Report Findings:** gives a high-level perspective on the full National Climate Assessment and sets out the report's 12 key findings. The Overview synthesizes and summarizes the ideas that the authors consider to be of greatest importance to the American people.
- **Our Changing Climate:** presents recent advances in climate change science, which includes discussions of extreme weather events, observed and projected changes in temperature and precipitation, and the uncertainties associated with these projections. Substantial additional material related to this chapter can be found in the Appendices.
- **Sectors:** focuses on climate change impacts for seven societal and environmental sectors: human health, water, energy, transportation, agriculture, forests, and ecosystems and biodiversity; six additional chapters consider the interactions among sectors (such as energy, water, and land use) in the context of a changing climate.
- **Regions:** assesses key impacts on U.S. regions – Northeast, Southeast and Caribbean, Midwest, Great Plains, Southwest, Northwest, Alaska, and Hawai'i and the U.S. affiliated Pacific Islands – as well as coastal areas, oceans, and marine resources.
- **Responses:** assesses the current state of responses to climate change, including adaptation, mitigation, and decision support activities.
- **Research Needs:** highlights major gaps in science and research to improve future assessments. New research is called for in climate science in support of assessments, climate impacts in regions and sectors, and adaptation, mitigation, and decision support.
- **Sustained Assessment Process:** describes an initial vision for and components of an ongoing, long-term assessment process.
- **Appendices:** Appendix 1 describes key aspects of the report process, with a focus on engagement; Appendix 2 describes the guidelines used in meeting the terms of the Federal Information Quality Act; Appendix 3 supplements the chapter on Our Changing Climate with an extended treatment of selected science issues; Appendix 4 provides answers to Frequently Asked Questions about climate change; Appendix 5 describes scenarios and models used in this assessment; and Appendix 6 describes possible topics for consideration in future assessments.

OVERARCHING PERSPECTIVES

Four overarching perspectives, derived from decades of observations, analysis, and experience, have helped to shape this report: 1) climate change is happening in the context of other ongoing changes across the U.S. and the globe; 2) climate change impacts can either be amplified or reduced by societal decisions; 3) climate change related impacts, vulnerabilities, and opportunities in the U.S. are linked to impacts and changes outside the United States, and vice versa; and 4) climate change can lead to dramatic tipping points in natural and social systems. These overarching perspectives are briefly discussed below.

Global Change Context

Climate change is one of a number of global changes affecting society, the environment, and the economy; others include population growth, land-use change, air and water pollution, and rising consumption of resources by a growing and wealthier global population. This perspective has implications for assessments of climate change impacts and the design of research questions at the national, regional, and local scales. This assessment explores some of the consequences of interacting factors by focusing on sets of crosscutting issues in a series of six chapters: Energy, Water, and Land Use; Biogeochemical Cycles; Indigenous Peoples, Lands, and Resources; Urban Systems, Infrastructure, and Vulnerability; Land Use and Land Cover Change; and Rural Communities. The assessment also includes discussions of how climate change impacts cascade through different sectors such as water and energy, and affect and are affected by land-use decisions. These and other interconnections greatly stress society's capacity to respond to climate-related crises that occur simultaneously or in rapid sequence.

Societal Choices

Because environmental, cultural, and socioeconomic systems are tightly coupled, climate change impacts can either be amplified or reduced by cultural and socioeconomic decisions. In many arenas, it is clear that societal decisions have substantial influence on the vulnerability of valued resources to climate change. For example, rapid population growth and development in coastal areas tends to amplify climate change related impacts. Recognition of these couplings, together with recognition of multiple sources of vulnerability, helps identify what information decision-makers need as they manage risks.

International Context

Climate change is a global phenomenon; the causes and the impacts involve energy-use, economic, and risk-management decisions across the globe. Impacts, vulnerabilities, and opportunities in the U.S. are related in complex and interactive ways with changes outside the United States, and vice versa. In order for U.S. concerns related to climate change to be addressed comprehensively, the international context must be considered. Foreign assistance, health, environmental quality objectives, and economic interests are all affected by climate changes experienced in other parts of the world. Although there is significantly more work to be done in this area, this report identifies some initial implications of global and international trends that can be more fully investigated in future assessments.

Thresholds, Tipping Points, and Surprises

While some climate changes will occur slowly and relatively gradually, others could be rapid and dramatic, leading to unexpected breaking points in natural and social systems. Although they have potentially large impacts, these breaking points or tipping points are difficult to predict, as there are many uncertainties about future conditions. These uncertainties and potential surprises come from a number of sources, including insufficient data associated with low probability/high consequence events, models that are not yet able to represent all the interactions of multiple stresses, incomplete understanding of physical climate mechanisms related to tipping points, and a multitude of issues associated with human behavior, risk management, and decision-making. Improving our ability to anticipate thresholds and tipping points can be helpful in developing effective climate change mitigation and adaptation strategies (Ch. 2: Our Changing Climate; Ch. 29: Research Needs; and Appendices 3 and 4).

RISK MANAGEMENT FRAMEWORK

Authors were asked to consider the science and information needs of decision-makers facing climate change risks to infrastructure, natural ecosystems, resources, communities, and other things of societal value. They were also asked to consider opportunities that climate change might present. For each region and sector, they were asked to assess a small number of key climate-related vulnerabilities of concern based on the risk (considering likelihood and consequence) of impacts. They were also asked to address the most important information needs of stakeholders, and to consider the decisions stakeholders are facing. The criteria provided for identifying key vulnerabilities in each sector or region included magnitude, timing, persistence/reversibility, scale, and distribution of impacts, likelihood whenever possible, importance of impacts (based on the perceptions of relevant parties), and the potential for adaptation. Authors were encouraged to think about these topics from both a quantitative and qualitative perspective and to consider the influence of multiple stresses whenever possible.

RESPONDING TO CLIMATE CHANGE

While the primary focus of this report is on the impacts of climate change in the United States, it also documents some of the actions society is taking or can take to respond. Responses to climate change fall into two broad categories. The first involves “mitigation” measures to reduce future climate change by reducing emissions of heat-trapping gases and particles, or increasing removal of carbon dioxide from the atmosphere. The second involves “adaptation” measures to improve society’s ability to cope with or avoid harmful impacts and take advantage of beneficial ones, now and in the future. At this point, both of these response activities are necessary to limit the magnitude and impacts of global climate change on the United States.

More effective mitigation measures can reduce the amount of climate change, and therefore reduce the need for future adaptation. This report underscores the effects of mitigation measures by comparing impacts resulting from higher versus lower emissions scenarios. This shows that choices made about emissions in the next few decades will have far-reaching consequences for climate change impacts throughout this century. Lower emissions will reduce the rate and lessen the magnitude of climate change and its impacts. Higher emissions will do the opposite.

While the report demonstrates the importance of mitigation as an essential part of the nation's climate change strategy, it does not evaluate mitigation technologies or policies or undertake an analysis of the effectiveness of various approaches. The range of mitigation responses being studied includes, but is not limited to, policies and technologies that lead to more efficient production and use of energy, increased use of non-carbon-emitting energy sources such as wind and solar power, and carbon capture and storage.

Adaptation actions are complementary to mitigation actions. They are focused on moderating harmful impacts of current and future climate variability and change and taking advantage of possible opportunities. While this report assesses the current state of adaptation actions and planning across the country in a general way, the implementation of adaptive actions is still nascent. A comprehensive assessment of actions taken, and of their effectiveness, is not yet possible. This report documents some of the actions currently being pursued to address impacts such as increased urban heat extremes and air pollution, and describes the challenges decision-makers face in planning for and implementing adaptation responses.

TRACEABLE ACCOUNTS: PROCESS AND CONFIDENCE

The "traceable accounts" that accompany each chapter: 1) document the process the authors used to reach the conclusions in their key messages; 2) provide additional information to reviewers and other readers about the quality of the information used; 3) allow traceability to resources; and 4) provide the level of confidence the authors have in the main findings of the chapters. The authors have assessed a wide range of information in the scientific literature and various technical reports. In assessing confidence, they have considered the strength and consistency of the observed evidence, the skill, range, and consistency of model projections, and insights from peer-reviewed sources.

When it is considered scientifically justified to report the likelihood of particular impacts within the range of possible outcomes, this report takes a plain-language approach to expressing the expert judgment of the author team based on the best available evidence. For example, an outcome termed "likely" has at least a two-thirds chance of occurring; an outcome termed "very likely" has more than a 90% chance. Key sources of information used to develop these characterizations are referenced.

1 OVERVIEW AND REPORT FINDINGS

Climate change is already affecting the American people in far-reaching ways. Certain types of extreme weather events with links to climate change have become more frequent and/or intense, including prolonged periods of heat, heavy downpours, and, in some regions, floods and droughts. In addition, warming is causing sea level to rise and glaciers and Arctic sea ice to melt, and oceans are becoming more acidic as they absorb carbon dioxide. These and other aspects of climate change are disrupting people's lives and damaging some sectors of our economy.

Climate Change: Present and Future

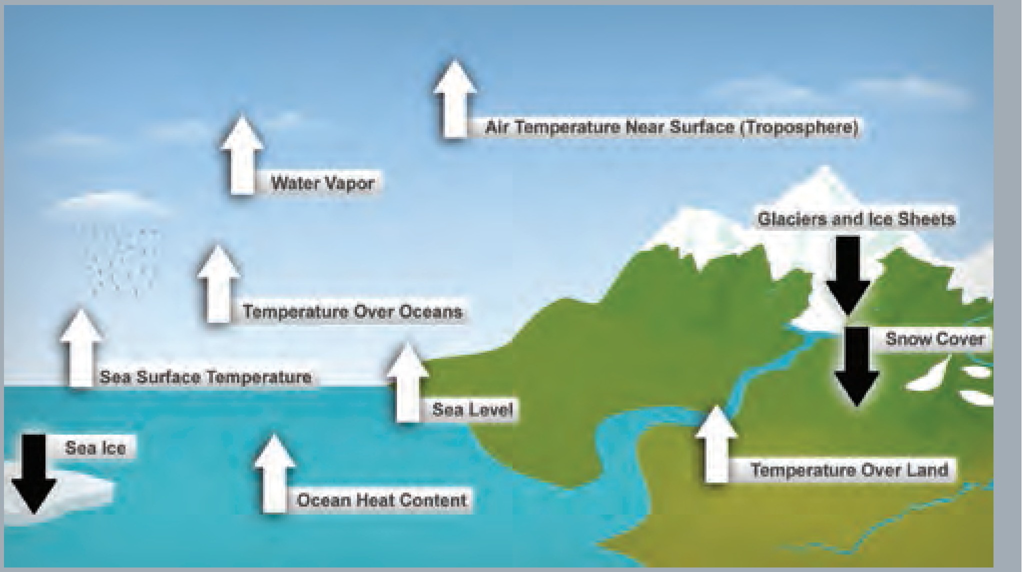
Evidence for climate change abounds, from the top of the atmosphere to the depths of the oceans. Scientists and engineers from around the world have meticulously collected this evidence, using satellites and networks of weather balloons, thermometers, buoys, and other observing systems. Evidence of climate change is also visible in the observed and measured changes in location and behavior of species and functioning of ecosystems. Taken together, this evidence tells an unambiguous story: the planet is warming, and over the last half century, this warming has been driven primarily by human activity.


© Frans Lanting/Corbis

Coal-fired power plants emit heat-trapping carbon dioxide to the atmosphere.

Multiple lines of independent evidence confirm that human activities are the primary cause of the global warming of the past 50 years. The burning of coal, oil, and gas, and clearing of forests have increased the concentration of carbon dioxide in the atmosphere by more than 40% since the Industrial Revolution, and it has been known for almost two centuries that this carbon dioxide traps heat. Methane and nitrous oxide emissions from agriculture and other human activities add to the atmospheric burden of heat-trapping gases. Data show that natural factors like the sun and volcanoes cannot have caused the warming observed over the past 50 years. Sensors on satellites have measured the sun's output with great accuracy and found no overall increase during the past half century. Large volcanic eruptions during this period, such as Mount Pinatubo in 1991, have exerted a short-term *cooling* influence. In fact, if not for human activities, global climate would actually have cooled slightly over the past 50 years. The pattern of temperature change through the layers of the atmosphere, with warming near the surface and cooling higher up in the stratosphere, further confirms that it is the buildup of heat-trapping gases (also known as "greenhouse gases") that has caused most of the Earth's warming over the past half century.

Ten Indicators of a Warming World

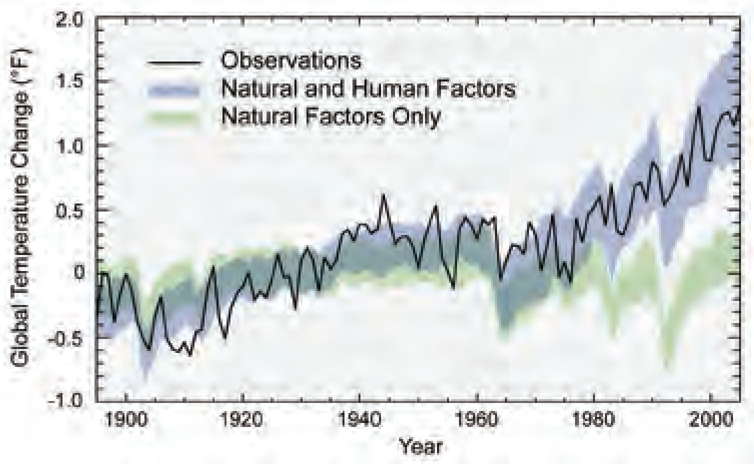


These are just some of the indicators measured globally over many decades that show that the Earth's climate is warming. White arrows indicate increasing trends; black arrows indicate decreasing trends. All the indicators expected to increase in a warming world are increasing, and all those expected to decrease in a warming world are decreasing. (Figure source: NOAA NCDC, based on data updated from Kennedy et al. 2010[a]).

Because human-induced warming is superimposed on a background of natural variations in climate, warming is not uniform over time. Short-term fluctuations in the long-term upward trend are thus natural and expected. For example, a recent slowing in the rate of surface air temperature rise appears to be related to cyclic changes in the oceans and in the sun's energy output, as well as a series of small volcanic eruptions and other factors. Nonetheless, global temperatures are still on the rise and are expected to rise further.

U.S. average temperature has increased by 1.3°F to 1.9°F since 1895, and most of this increase has occurred since 1970. The most recent decade was the nation's and the world's hottest on record, and 2012 was the hottest year on record in the continental United States. All U.S. regions have experienced warming in recent decades, but the extent of warming has not been uniform. In general, temperatures are rising more quickly in the north. Alaskans have experienced some of the largest increases in temperature between 1970 and the present. People living in the Southeast have experienced some of the smallest temperature increases over this period.

Separating Human and Natural Influences on Climate

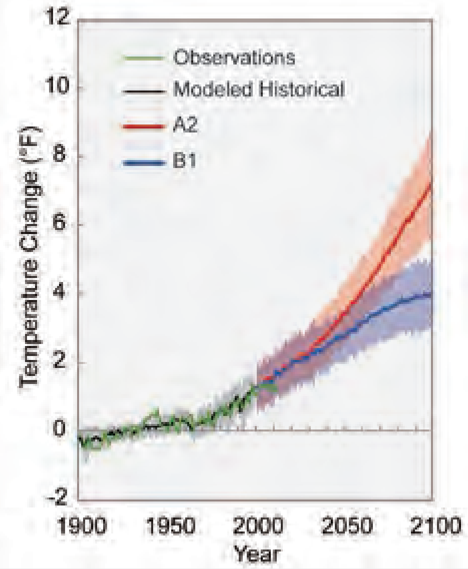


The green band shows how global average temperature would have changed over the last century due to natural forces alone, as simulated by climate models. The blue band shows model simulations of the effects of human and natural forces (including solar and volcanic activity) combined. The black line shows the actual observed global average temperatures. Only with the inclusion of human influences can models reproduce the observed temperature changes. (Figure source: adapted from Huber and Knutti 2012[b]).

Temperatures are projected to rise another 2°F to 4°F in most areas of the United States over the next few decades. Reductions in some short-lived human-induced emissions that contribute to warming, such as black carbon (soot) and methane, could reduce some of the projected warming over the next couple of decades, because, unlike carbon dioxide, these gases and particles have relatively short atmospheric lifetimes.

The amount of warming projected beyond the next few decades is directly linked to the cumulative global emissions of heat-trapping gases and particles. By the end of this century, a roughly 3°F to 5°F rise is projected under a lower emissions scenario, which would require substantial reductions in emissions (referred to as the "B1 scenario"), and a 5°F to 10°F rise for a higher emissions scenario assuming continued increases in emissions, predominantly from fossil fuel combustion (referred to as the "A2 scenario"). These projections are based on results from 16 climate models that used the two emissions scenarios in a formal intermodel comparison study. The range of model projections for each emissions scenario is the result of the differences in the ways the models represent key factors such as water vapor, ice and snow reflectivity, and clouds, which can either dampen or amplify the initial effect of human influences on temperature. The net effect of these feedbacks is expected to amplify warming. More information about the models and scenarios used in this report can be found in Appendix 5 of the full report.[1]

Projected Global Temperature Change



Different amounts of heat-trapping gases released into the atmosphere by human activities produce different projected increases in Earth's temperature. The lines on the graph represent a central estimate of global average temperature rise (relative to the 1901-1960 average) for the two main scenarios used in this report. A2 assumes continued increases in emissions throughout this century, and B1 assumes significant emissions reductions, though not due explicitly to climate change policies. Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. In both cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. (Figure source: NOAA NCDC / CICS-NC).

Prolonged periods of high temperatures and the persistence of high nighttime temperatures have increased in many locations (especially in urban areas) over the past half century. High nighttime temperatures have widespread impacts because people, livestock, and wildlife get no respite from the heat. In some regions, prolonged periods of high temperatures associated with droughts contribute to conditions that lead to larger wildfires and longer fire seasons. As expected in a warming climate, recent trends show that extreme heat is becoming more common, while extreme cold is becoming less common. Evidence indicates that the human influence on climate has already roughly doubled the probability of extreme heat events such as the record-breaking summer heat experienced in 2011 in Texas and Oklahoma. The incidence of record-breaking high temperatures is projected to rise.[2]

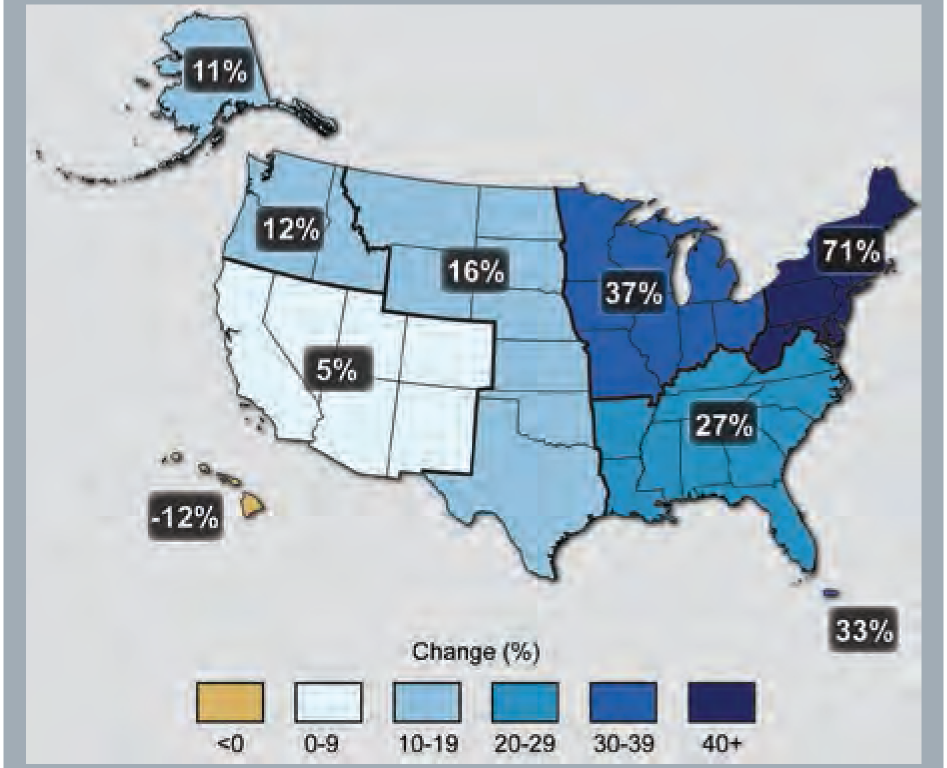
Human-induced climate change means much more than just hotter weather. Increases in ocean and freshwater temperatures, frost-free days, and heavy downpours have all been documented. Global sea level has risen, and there have been large reductions in snow-cover extent, glaciers, and sea ice. These changes and other climatic changes have affected and will continue to affect human health, water supply, agriculture, transportation, energy, coastal areas, and many other sectors of society, with increasingly adverse impacts on the American economy and quality of life.[3]

Some of the changes discussed in this report are common to many regions. For example, large increases in heavy precipitation have occurred in the Northeast, Midwest, and Great Plains, where heavy downpours have frequently led to runoff that exceeded the capacity of storm drains and levees, and caused flooding events and accelerated erosion. Other impacts, such as those associated with the rapid thawing of permafrost in Alaska, are unique to a particular U.S. region. Permafrost thawing is causing extensive damage to infrastructure in our nation's largest state.[4]

Some impacts that occur in one region ripple beyond that region. For example, the dramatic decline of summer sea ice in the Arctic – a loss of ice cover roughly equal to half the area of the continental United States – exacerbates global warming by reducing the reflectivity of Earth's surface and increasing the amount of heat absorbed. Similarly, smoke from wildfires in one location can contribute to poor air quality in faraway regions, and evidence suggests that particulate matter can affect atmospheric properties and therefore weather patterns. Major storms and the higher storm surges exacerbated by sea level rise that hit the Gulf Coast affect the entire country through their cascading effects on oil and gas production and distribution.[5]

Water expands as it warms, causing global sea levels to rise; melting of land-based ice also raises sea level by adding water to the oceans. Over the past century, global average sea level has risen by about 8 inches. Since 1992, the rate of global sea level rise measured by satellites has been roughly twice the rate observed over the last century, providing evidence of acceleration. Sea level rise, combined with coastal storms, has increased the risk of erosion, storm surge damage, and flooding for coastal communities, especially along the Gulf Coast, the Atlantic seaboard, and in Alaska. Coastal infrastructure, including roads, rail lines, energy infrastructure, airports, port facilities, and military bases, are increasingly at risk from sea level rise and damaging storm surges. Sea level is projected to rise by another 1 to 4 feet in this century, although the rise in sea level in specific regions is expected to vary from this global average for a number of reasons. A wider range of scenarios,

Observed Change in Very Heavy Precipitation

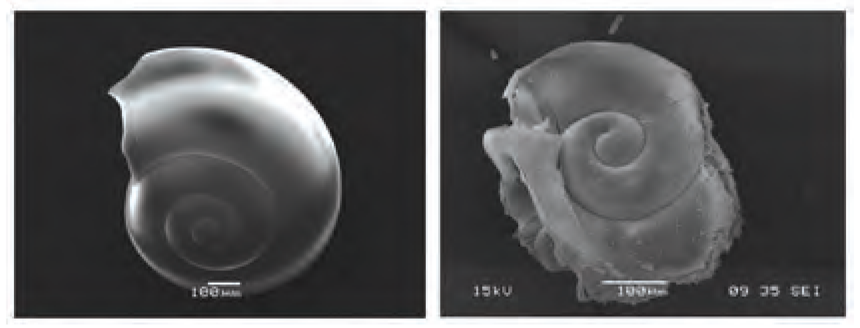


Percent changes in the amount of precipitation falling in very heavy events (the heaviest 1%) from 1958 to 2012 for each region. There is a clear national trend toward a greater amount of precipitation being concentrated in very heavy events, particularly in the Northeast and Midwest. (Figure source: updated from Karl et al. 2009[c]).

from 8 inches to more than 6 feet by 2100, has been used in risk-based analyses in this report. In general, higher emissions scenarios that lead to more warming would be expected to lead to higher amounts of sea level rise. The stakes are high, as nearly five million Americans and hundreds of billions of dollars of property are located in areas that are less than four feet above the local high-tide level.[6]

In addition to causing changes in climate, increasing levels of carbon dioxide from the burning of fossil fuels and other human activities have a direct effect on the world's oceans. Carbon dioxide interacts with ocean water to form carbonic acid, increasing the ocean's acidity. Ocean surface waters have become 30% more acidic over the last 250 years as they have absorbed large amounts of carbon dioxide from the atmosphere. This ocean acidification makes water more corrosive, reducing the capacity of marine organisms with shells or skeletons made of calcium carbonate (such as corals, krill, oysters, clams, and crabs) to survive, grow, and reproduce, which in turn will affect the marine food chain.[7]

Shells Dissolve in Acidified Ocean Water

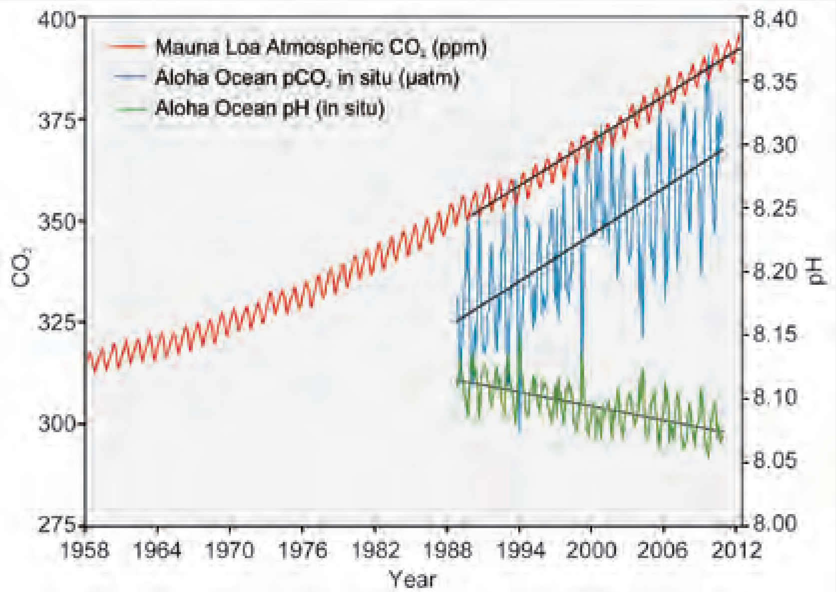


Pteropods, or "sea butterflies," are eaten by a variety of marine species ranging from tiny krill to salmon to whales. The photos show what happens to a pteropod's shell in seawater that is too acidic. On the left is a shell from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod in a region where the water is more acidic. (Figure source: (left) Bednaršek et al. 2012[e] (right) Nina Bednaršek).

Widespread Impacts

Impacts related to climate change are already evident in many regions and sectors and are expected to become increasingly disruptive across the nation throughout this century and beyond. Climate changes interact with other environmental and societal factors in ways that can either moderate or intensify these impacts.

As Oceans Absorb CO_2 They Become More Acidic



The correlation between rising levels of carbon dioxide in the atmosphere (red) with rising carbon dioxide levels (blue) and falling pH in the ocean (green). As carbon dioxide accumulates in the ocean, the water becomes more acidic (the pH declines). (Figure source: modified from Feely et al. 2009[d]).

Observed and projected climate change impacts vary across the regions of the United States. Selected impacts emphasized in the regional chapters are shown below, and many more are explored in detail in this report.

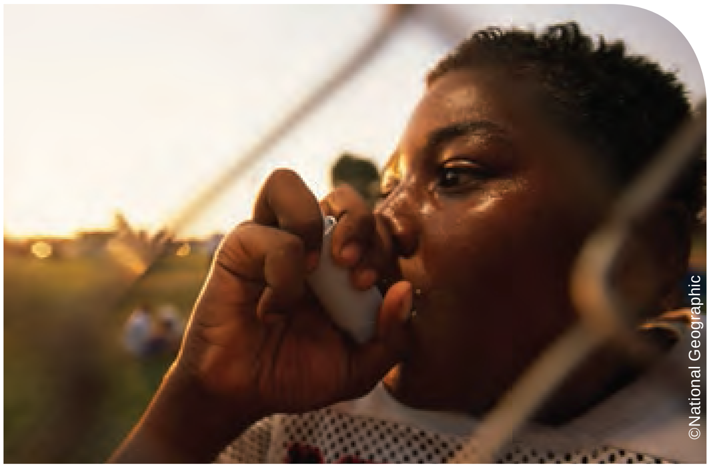
	Northeast	Communities are affected by heat waves, more extreme precipitation events, and coastal flooding due to sea level rise and storm surge.
	Southeast and Caribbean	Decreased water availability, exacerbated by population growth and land-use change, causes increased competition for water. There are increased risks associated with extreme events such as hurricanes.
	Midwest	Longer growing seasons and rising carbon dioxide levels increase yields of some crops, although these benefits have already been offset in some instances by occurrence of extreme events such as heat waves, droughts, and floods.
	Great Plains	Rising temperatures lead to increased demand for water and energy and impacts on agricultural practices.
	Southwest	Drought and increased warming foster wildfires and increased competition for scarce water resources for people and ecosystems.
	Northwest	Changes in the timing of streamflow related to earlier snowmelt reduce the supply of water in summer, causing far-reaching ecological and socioeconomic consequences.
	Alaska	Rapidly receding summer sea ice, shrinking glaciers, and thawing permafrost cause damage to infrastructure and major changes to ecosystems. Impacts to Alaska Native communities increase.
	Hawai‘i and Pacific Islands	Increasingly constrained freshwater supplies, coupled with increased temperatures, stress both people and ecosystems and decrease food and water security.
	Coasts	Coastal lifelines, such as water supply infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, and other climate-related changes.
	Oceans	The oceans are currently absorbing about a quarter of human-caused carbon dioxide emissions to the atmosphere and over 90% of the heat associated with global warming, leading to ocean acidification and the alteration of marine ecosystems.

Some climate changes currently have beneficial effects for specific sectors or regions. For example, current benefits of warming include longer growing seasons for agriculture and longer ice-free periods for shipping on the Great Lakes. At the same time, however, longer growing seasons, along with higher temperatures and carbon dioxide levels, can increase pollen production, intensifying and lengthening the allergy season. Longer ice-free periods on the Great Lakes can result in more lake-effect snowfalls.

Sectors affected by climate changes include agriculture, water, human health, energy, transportation, forests, and ecosystems. Climate change poses a major challenge to U.S. agriculture because of the critical dependence of agricultural systems on climate. Climate change has the potential to both positively and negatively affect the location, timing, and productivity of crop, livestock, and fishery systems at local, national, and global scales. The United States produces nearly $330 billion per year in agricultural commodities. This productivity is vulnerable to direct impacts on crops and livestock from changing climate conditions and extreme weather events and indirect impacts through increasing pressures from pests and pathogens. Climate change will also alter the stability of food supplies and create new food security challenges for the United States as the world seeks to feed nine billion people by 2050. While the agriculture sector has proven to be adaptable to a range of stresses, as evidenced by continued growth in production and efficiency across the United States, climate change poses a new set of challenges.[8]

Certain groups of people are more vulnerable to the range of climate change related health impacts, including the elderly, children, the poor, and the sick.

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease water quality in many ways. Here, middle school students in Colorado test water quality.



Climate change can exacerbate respiratory and asthma-related conditions through increases in pollen, ground-level ozone, and wildfire smoke.

Water quality and quantity are being affected by climate change. Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses. Water quality is also diminishing in many areas, particularly due to sediment and contaminant concentrations after heavy downpours. Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands. In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.[9]

Climate change affects human health in many ways. For example, increasingly frequent and intense heat events lead to more heat-related illnesses and deaths and, over time, worsen drought and wildfire risks, and intensify air pollution. Increasingly frequent extreme precipitation and associated flooding can lead to injuries and increases in waterborne disease. Rising sea surface temperatures have been linked with increasing levels and ranges of diseases. Rising sea levels intensify coastal flooding and storm surge, and thus exacerbate threats to public safety during storms. Certain groups of people are more vulnerable to the range of climate change related health impacts, including the elderly, children, the poor, and the sick. Others are vulnerable because of where they live, including those in floodplains, coastal zones, and some urban areas. Improving and properly supporting the public health infrastructure will be critical to managing the potential health impacts of climate change.[10]

Climate change also affects the living world, including people, through changes in ecosystems and biodiversity. Ecosystems provide a rich array of benefits and services to humanity, including habitat for fish and wildlife, drinking water storage and filtration, fertile soils for growing crops, buffering against a range of stressors including climate change impacts, and aesthetic and cultural values. These benefits are not always easy to quantify, but they support jobs, economic growth, health, and human well-being. Climate change driven disruptions to ecosystems have direct and indirect human impacts, including reduced water supply and quality, the loss of iconic species and landscapes, effects on food chains and the timing and success of species migrations, and the potential for extreme weather and climate events to destroy or degrade the ability of ecosystems to provide societal benefits.[11]

> The amount of future climate change will still largely be determined by choices society makes about emissions.

Human modifications of ecosystems and landscapes often increase their vulnerability to damage from extreme weather events, while simultaneously reducing their natural capacity to moderate the impacts of such events. For example, salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure, such as roads and buildings, against storm surges. The loss of these natural buffers due to coastal development, erosion, and sea level rise increases the risk of catastrophic damage during or after extreme weather events. Although floodplain wetlands are greatly reduced from their historical extent, those that remain still absorb floodwaters and reduce the effects of high flows on river-margin lands. Extreme weather events that produce sudden increases in water flow, often carrying debris and pollutants, can decrease the natural capacity of ecosystems to cleanse contaminants.[12]

The climate change impacts being felt in the regions and sectors of the United States are affected by global trends and economic decisions. In an increasingly interconnected world, U.S. vulnerability is linked to impacts in other nations. It is thus difficult to fully evaluate the impacts of climate change on the United States without considering consequences of climate change elsewhere.

Response Options

As the impacts of climate change are becoming more prevalent, Americans face choices. Especially because of past emissions of long-lived heat-trapping gases, some additional climate change and related impacts are now unavoidable. This is due to the long-lived nature of many of these gases, as well as the amount of heat absorbed and retained by the oceans and other responses within the climate system. The amount of future climate change, however, will still largely be determined by choices society makes about emissions. Lower emissions of heat-trapping gases and particles mean less future warming and less-severe impacts; higher emissions mean more warming and more severe impacts. Efforts to limit emissions or increase carbon uptake fall into a category of response options known as “mitigation,” which refers to reducing the amount and speed of future climate change by reducing emissions of heat-trapping gases or removing carbon dioxide from the atmosphere.[13]

The other major category of response options is known as “adaptation,” and refers to actions to prepare for and adjust to new conditions, thereby reducing harm or taking advantage of new opportunities. Mitigation and adaptation actions are linked in multiple ways, including that effective mitigation reduces the need for adaptation in the future. Both are essential parts of a comprehensive climate change response strategy. The threat of irreversible impacts makes the timing of mitigation efforts particularly critical. This report includes chapters on Mitigation, Adaptation, and Decision Support that offer an overview of the options and activities being planned or implemented around the country as local, state, federal, and tribal governments, as well as businesses, organizations, and individuals begin to respond to climate change. These chapters conclude that while response actions are under development, current implementation efforts are insufficient to avoid increasingly negative social, environmental, and economic consequences.[14]

Large reductions in global emissions of heat-trapping gases, similar to the lower emissions scenario (B1) analyzed in this assessment, would reduce the risks of some of the worst impacts of climate change. Some targets called for in international climate negotiations to date would require even larger reductions than those outlined in the B1 scenario. Meanwhile, global emissions are still rising and are on a path to be even higher than the high emissions scenario (A2) analyzed in this report. The recent U.S. contribution to annual global emissions is about 18%, but the U.S. contribution to cumulative global emissions over the last century is much higher. Carbon dioxide lasts for a long time in the atmosphere, and it is the cumulative carbon emissions that determine the amount of global climate change. After decades of increases, U.S. CO_2 emissions from energy use (which account for 97% of total U.S. emissions) declined by around 9% between 2008 and 2012, largely due to a shift from coal to less CO_2-intensive natural gas for electricity production. Governmental actions in city, state, regional, and federal programs to promote energy efficiency have also contributed to reducing U.S. carbon emissions. Many, if not most of these programs are motivated by other policy objectives, but some are directed specifically at greenhouse gas emissions.

These U.S. actions and others that might be undertaken in the future are described in the Mitigation chapter of this report. Over the remainder of this century, aggressive and sustained greenhouse gas emission reductions by the United States and by other nations would be needed to reduce global emissions to a level consistent with the lower scenario (B1) analyzed in this assessment.[15]

With regard to adaptation, the pace and magnitude of observed and projected changes emphasize the need to be prepared for a wide variety and intensity of impacts. Because of the growing influence of human activities, the climate of the past is not a good basis for future planning. For example, building codes and landscaping ordinances could be updated to improve energy efficiency, conserve water supplies, protect against insects that spread disease (such as dengue fever), reduce susceptibility to heat stress, and improve protection against extreme events. The fact that climate change impacts are increasing points to the urgent need to develop and refine approaches that enable decision-making and increase flexibility and resilience in the face of ongoing and future impacts. Reducing non-climate-related stresses that contribute to existing vulnerabilities can also be an effective approach to climate change adaptation.[16]

Adaptation can involve considering local, state, regional, national, and international jurisdictional objectives. For example, in managing water supplies to adapt to a changing climate, the implications of international treaties should be considered in the context of managing the Great Lakes, the Columbia River, and the Colorado River to deal with increased drought risk. Both “bottom up” community planning and “top down” national strategies may help regions deal with impacts such as increases in electrical brownouts, heat stress, floods, and wildfires.[17]

Proactively preparing for climate change can reduce impacts while also facilitating a more rapid and efficient response to changes as they happen. Such efforts are beginning at the federal, regional, state, tribal, and local levels, and in the corporate and non-governmental sectors, to build adaptive capacity and resilience to climate change impacts. Using scientific information to prepare for climate changes in advance can provide economic opportunities, and proactively managing the risks can reduce impacts and costs over time.[18]

There are a number of areas where improved scientific information or understanding would enhance the capacity to estimate future climate change impacts. For example, knowledge of the mechanisms controlling the rate of ice loss in Greenland and Antarctica is limited, making it difficult for scientists to narrow the range of expected future sea level rise. Improved understanding of ecological and social responses to climate change is needed, as is understanding of how ecological and social responses will interact.[19]

A sustained climate assessment process could more efficiently collect and synthesize the rapidly evolving science and help supply timely and relevant information to decision-makers. Results from all of these efforts could continue to deepen our understanding of the interactions of human and natural systems in the context of a changing climate, enabling society to effectively respond and prepare for our future.[20]

The cumulative weight of the scientific evidence contained in this report confirms that climate change is affecting the American people now, and that choices we make will affect our future and that of future generations.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FEMA

Cities providing transportation options including bike lanes, buildings designed with energy saving features such as green roofs, and houses elevated to allow storm surges to pass underneath are among the many response options being pursued around the country.

Report Findings

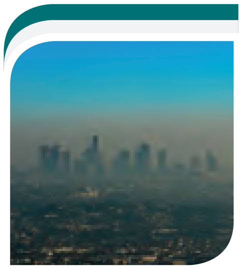
These findings distill important results that arise from this National Climate Assessment. They do not represent a full summary of all of the chapters' findings, but rather a synthesis of particularly noteworthy conclusions.

1. Global climate is changing and this is apparent across the United States in a wide range of observations. The global warming of the past 50 years is primarily due to human activities, predominantly the burning of fossil fuels.

Many independent lines of evidence confirm that human activities are affecting climate in unprecedented ways. U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the warmest on record. Because human-induced warming is superimposed on a naturally varying climate, rising temperatures are not evenly distributed across the country or over time.[21] See page 18.

2. Some extreme weather and climate events have increased in recent decades, and new and stronger evidence confirms that some of these increases are related to human activities.

Changes in extreme weather events are the primary way that most people experience climate change. Human-induced climate change has already increased the number and strength of some of these extreme events. Over the last 50 years, much of the United States has seen an increase in prolonged periods of excessively high temperatures, more heavy downpours, and in some regions, more severe droughts.[22] See page 24.



3. Human-induced climate change is projected to continue, and it will accelerate significantly if global emissions of heat-trapping gases continue to increase.

Heat-trapping gases already in the atmosphere have committed us to a hotter future with more climate-related impacts over the next few decades. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases that human activities emit globally, now and in the future.[23] See page 28.

4. Impacts related to climate change are already evident in many sectors and are expected to become increasingly disruptive across the nation throughout this century and beyond.

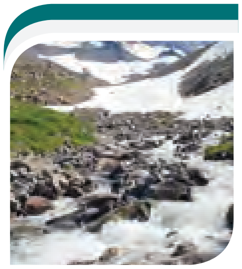
Climate change is already affecting societies and the natural world. Climate change interacts with other environmental and societal factors in ways that can either moderate or intensify these impacts. The types and magnitudes of impacts vary across the nation and through time. Children, the elderly, the sick, and the poor are especially vulnerable. There is mounting evidence that harm to the nation will increase substantially in the future unless global emissions of heat-trapping gases are greatly reduced.[24] See page 32.

5. Climate change threatens human health and well-being in many ways, including through more extreme weather events and wildfire, decreased air quality, and diseases transmitted by insects, food, and water.

Climate change is increasing the risks of heat stress, respiratory stress from poor air quality, and the spread of waterborne diseases. Extreme weather events often lead to fatalities and a variety of health impacts on vulnerable populations, including impacts on mental health, such as anxiety and post-traumatic stress disorder. Large-scale changes in the environment due to climate change and extreme weather events are increasing the risk of the emergence or reemergence of health threats that are currently uncommon in the United States, such as dengue fever.[25] See page 34.

6. Infrastructure is being damaged by sea level rise, heavy downpours, and extreme heat; damages are projected to increase with continued climate change.

Sea level rise, storm surge, and heavy downpours, in combination with the pattern of continued development in coastal areas, are increasing damage to U.S. infrastructure including roads, buildings, and industrial facilities, and are also increasing risks to ports and coastal military installations. Flooding along rivers, lakes, and in cities following heavy downpours, prolonged rains, and rapid melting of snowpack is exceeding the limits of flood protection infrastructure designed for historical conditions. Extreme heat is damaging transportation infrastructure such as roads, rail lines, and airport runways.[26] See page 38.



7. Water quality and water supply reliability are jeopardized by climate change in a variety of ways that affect ecosystems and livelihoods.

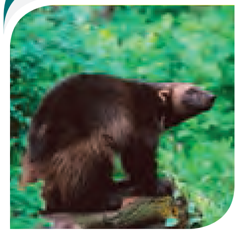
Surface and groundwater supplies in some regions are already stressed by increasing demand for water as well as declining runoff and groundwater recharge. In some regions, particularly the southern part of the country and the Caribbean and Pacific Islands, climate change is increasing the likelihood of water shortages and competition for water among its many uses. Water quality is diminishing in many areas, particularly due to increasing sediment and contaminant concentrations after heavy downpours.[27] See page 42.

8. Climate disruptions to agriculture have been increasing and are projected to become more severe over this century.

Some areas are already experiencing climate-related disruptions, particularly due to extreme weather events. While some U.S. regions and some types of agricultural production will be relatively resilient to climate change over the next 25 years or so, others will increasingly suffer from stresses due to extreme heat, drought, disease, and heavy downpours. From mid-century on, climate change is projected to have more negative impacts on crops and livestock across the country – a trend that could diminish the security of our food supply.[28] See page 46.

9. Climate change poses particular threats to Indigenous Peoples' health, well-being, and ways of life.

Chronic stresses such as extreme poverty are being exacerbated by climate change impacts such as reduced access to traditional foods, decreased water quality, and increasing exposure to health and safety hazards. In parts of Alaska, Louisiana, the Pacific Islands, and other coastal locations, climate change impacts (through erosion and inundation) are so severe that some communities are already relocating from historical homelands to which their traditions and cultural identities are tied. Particularly in Alaska, the rapid pace of temperature rise, ice and snow melt, and permafrost thaw are significantly affecting critical infrastructure and traditional livelihoods.[29] See page 48.



10. Ecosystems and the benefits they provide to society are being affected by climate change. The capacity of ecosystems to buffer the impacts of extreme events like fires, floods, and severe storms is being overwhelmed.

Climate change impacts on biodiversity are already being observed in alteration of the timing of critical biological events such as spring bud burst and substantial range shifts of many species. In the longer term, there is an increased risk of species extinction. These changes have social, cultural, and economic effects. Events such as droughts, floods, wildfires, and pest outbreaks associated with climate change (for example, bark beetles in the West) are already disrupting ecosystems. These changes limit the capacity of ecosystems, such as forests, barrier beaches, and wetlands, to continue to play important roles in reducing the impacts of these extreme events on infrastructure, human communities, and other valued resources.[30] See page 50.

11. Ocean waters are becoming warmer and more acidic, broadly affecting ocean circulation, chemistry, ecosystems, and marine life.

More acidic waters inhibit the formation of shells, skeletons, and coral reefs. Warmer waters harm coral reefs and alter the distribution, abundance, and productivity of many marine species. The rising temperature and changing chemistry of ocean water combine with other stresses, such as overfishing and coastal and marine pollution, to alter marine-based food production and harm fishing communities.[31] See page 58.

12. Planning for adaptation (to address and prepare for impacts) and mitigation (to reduce future climate change, for example by cutting emissions) is becoming more widespread, but current implementation efforts are insufficient to avoid increasingly negative social, environmental, and economic consequences.

Actions to reduce emissions, increase carbon uptake, adapt to a changing climate, and increase resilience to impacts that are unavoidable can improve public health, economic development, ecosystem protection, and quality of life.[32] See page 62.

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Numbered references for the Overview indicate the chapters that provide supporting evidence for the reported conclusions.

1. Ch. 2.
2. Ch. 2, 3, 6, 9, 20.
3. Ch. 2, 3, 4, 5, 6, 9, 10, 12, 16, 20, 24, 25.
4. Ch. 2, 12, 16, 18, 19, 20, 21, 22, 23.
5. Ch. 2, 4, 12, 16, 17, 18, 19, 20, 22, 25.
6. Ch. 2, 4, 5, 10, 12, 16, 17, 20, 22, 25.
7. Ch. 2, 12, 23, 24, 25.
8. Ch. 2, 12, 13, 14, 18, 19.
9. Ch. 2, 3, 12, 16, 17, 18, 19, 20, 21, 23.
10. Ch. 2, 9, 11, 12, 13, 16, 18, 19, 20, 25.
11. Ch. 3, 6, 8, 12, 14, 23, 24, 25.
12. Ch. 3, 7, 8, 25.
13. Ch. 2, 26, 27.
14. Ch. 26, 27, 28.
15. Ch. 2, 4, 27.
16. Ch. 2, 3, 5, 9, 11, 12, 13, 25, 26, 27, 28.
17. Ch. 3, 7, 9, 10, 12, 18, 20, 21, 26, 28.
18. Ch. 28.
19. Ch. 29, Appendix 6.
20. Ch. 30.
21. Ch. 2, Appendices 3 and 4.
22. Ch. 2, 16, 17, 18, 19, 20, 23, Appendices 3 and 4.
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27. Ch. 2, 3, 12, 16, 17, 18, 19, 20, 21, 23.
28. Ch. 2, 6, 12, 13, 14, 18, 19.
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Climate Change Impacts in the United States

CHAPTER 2
OUR CHANGING CLIMATE

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On the Web: http://nca2014.globalchange.gov/report/our-changing-climate/introduction

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

2 OUR CHANGING CLIMATE

Key Messages

1. **Global climate is changing and this change is apparent across a wide range of observations. The global warming of the past 50 years is primarily due to human activities.**

2. **Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.**

3. **U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the nation's warmest on record. Temperatures in the United States are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.**

4. **The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.**

5. **Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.**

6. **Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.**

7. **There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense, and cold waves less intense everywhere.**

8. **The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.**

9. **Winter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, are uncertain and are being studied intensively.**

Continued ▼

KEY MESSAGES (CONTINUED)

10. Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

11. Rising temperatures are reducing ice volume and surface extent on land, lakes, and sea. This loss of ice is expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century.

12. The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems.

This chapter summarizes how climate is changing, why it is changing, and what is projected for the future. While the focus is on changes in the United States, the need to provide context sometimes requires a broader geographical perspective. Additional geographic detail is presented in the regional chapters of this report. Further details on the topics covered by this chapter are provided in the Climate Science Supplement and Frequently Asked Questions Appendices.

Since the second National Climate Assessment was published in 2009,[1] the climate has continued to change, with resulting effects on the United States. The trends described in the 2009 report have continued, and our understanding of the data and ability to model the many facets of the climate system have increased substantially. Several noteworthy advances are mentioned in the box below.

The 12 key messages presented above are repeated below, together with supporting evidence for those messages. The discussion of each key message begins with a summary of recent variations or trends, followed by projections of the corresponding changes for the future.

WHAT'S NEW?

- Continued warming and an increased understanding of the U.S. temperature record, as well as multiple other sources of evidence, have strengthened our confidence in the conclusions that the warming trend is clear and primarily the result of human activities. For the contiguous United States, the last decade was the warmest on record, and 2012 was the warmest year on record.
- Heavy precipitation and extreme heat events are increasing in a manner consistent with model projections; the risks of such extreme events will rise in the future.
- The sharp decline in summer Arctic sea ice has continued, is unprecedented, and is consistent with human-induced climate change. A new record for minimum area of Arctic sea ice was set in 2012.
- A longer and better-quality history of sea level rise has increased confidence that recent trends are unusual and human-induced. Limited knowledge of ice sheet dynamics leads to a broad range for projected sea level rise over this century.
- New approaches to building scenarios of the future have allowed for investigations of the implications of larger reductions in heat trapping gas emissions than examined previously.

REFERENCE PERIODS FOR GRAPHS

Many of the graphs in this report illustrate historical changes and future trends in climate compared to some reference period, with the choice of this period determined by the purpose of the graph and the availability of data. The great majority of graphs are based on one of two reference periods. The period 1901-1960 is used for graphs that illustrate past changes in climate conditions, whether in observations or in model simulations. The choice of 1960 as the ending date of this period was based on past changes in human influences on the climate system. Human-induced forcing exhibited a slow rise during the early part of the last century but then accelerated after 1960.[2] Thus, these graphs highlight observed changes in climate during the period of rapid increase in human-caused forcing and also reveal how well climate models simulate these observed changes. The beginning date of 1901 was chosen because earlier historical observations are less reliable and because many climate model simulations begin in 1900 or 1901. The other commonly used reference period is 1971-2000, which is consistent with the World Meteorological Organization's recommended use of 30-year periods for climate statistics. This is used for graphs that illustrate projected future changes simulated by climate models. The purpose of these graphs is to show projected changes compared to a period that people have recently experienced and can remember; thus, the most recent available 30-year period was chosen (the historical period simulated by the CMIP3 models ends in 1999 or 2000).

Key Message 1: Observed Climate Change

Global climate is changing and this change is apparent across a wide range of observations. The global warming of the past 50 years is primarily due to human activities.

Climate is defined as long-term averages and variations in weather measured over a period of several decades. The Earth's climate system includes the land surface, atmosphere, oceans, and ice. Many aspects of the global climate are changing rapidly, and the primary drivers of that change are human in origin. Evidence for changes in the climate system abounds, from the top of the atmosphere to the depths of the oceans (Figure 2.1).[3] Scientists and engineers from around the world have compiled this evidence using satellites, weather balloons, thermometers at surface stations, and many other types of observing systems that monitor the Earth's weather and climate. The sum total of this evidence tells an unambiguous story: the planet is warming.

Ten Indicators of a Warming World

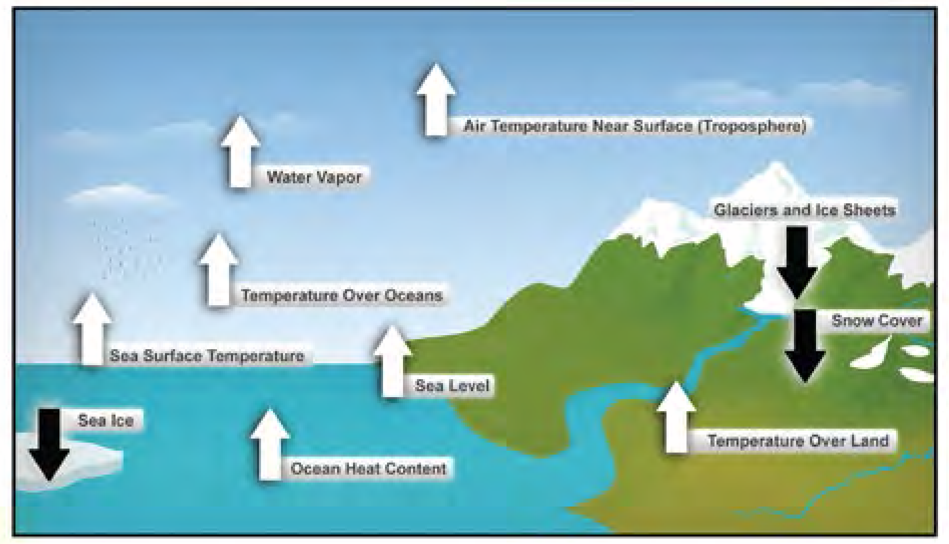

Figure 2.1. These are just some of the indicators measured globally over many decades that show that the Earth's climate is warming. White arrows indicate increasing trends, and black arrows indicate decreasing trends. All the indicators expected to increase in a warming world are, in fact, increasing, and all those expected to decrease in a warming world are decreasing. (Figure source: NOAA NCDC based on data updated from Kennedy et al. 2010[3]).

Temperatures at the surface, in the troposphere (the active weather layer extending up to about 5 to 10 miles above the ground), and in the oceans have all increased over recent decades (Figure 2.2). Consistent with our scientific understanding, the largest increases in temperature are occurring closer to the poles, especially in the Arctic. Snow and ice cover have decreased in most areas. Atmospheric water vapor is increasing in the lower atmosphere, because a warmer atmosphere can hold more water. Sea levels are also increasing (see Key Message 10). Changes in other climate-relevant indicators such as growing season length have been observed in many areas. Worldwide, the observed changes in average conditions have been accompanied by increasing trends in extremes of heat and heavy precipitation events, and decreases in extreme cold.[4]

Natural drivers of climate cannot explain the recent observed warming. Over the last five decades, natural factors (solar forcing and volcanoes) alone would actually have led to a slight cooling (see Figure 2.3).[5]

The majority of the warming at the global scale over the past 50 years can only be explained by the effects of human influences,[5,6,7] especially the emissions from burning fossil fuels (coal, oil, and natural gas) and from deforestation. The emissions from human influences that are affecting climate include heat-trapping gases such as carbon dioxide (CO_2), methane, and nitrous oxide, and particles such as black carbon (soot), which has a warming influence, and sulfates, which have an overall cooling influence (see Appendix 3: Climate Science Supplement for further discussion).[8,9] In addition to human-induced global climate change, local climate can also be affected by other human factors (such as crop irrigation) and natural variability (for example, Ashley et al. 2012; DeAngelis et al. 2010; Degu et al. 2011; Lo and Famiglietti 2013[10]).

The conclusion that human influences are the primary driver of recent climate change is based on multiple lines of independent evidence. The first line of evidence is our fundamental understanding of how certain gases trap heat, how the climate system responds to increases in these gases, and how other human and natural factors influence climate. The second line of evidence is from reconstructions of past climates using evidence such as tree rings, ice cores, and corals. These show that global surface temperatures over the last several decades are clearly unusual, with the last decade (2000-2009) warmer than any time in at least the last 1300 years and perhaps much longer.[11]

Global Temperature and Carbon Dioxide

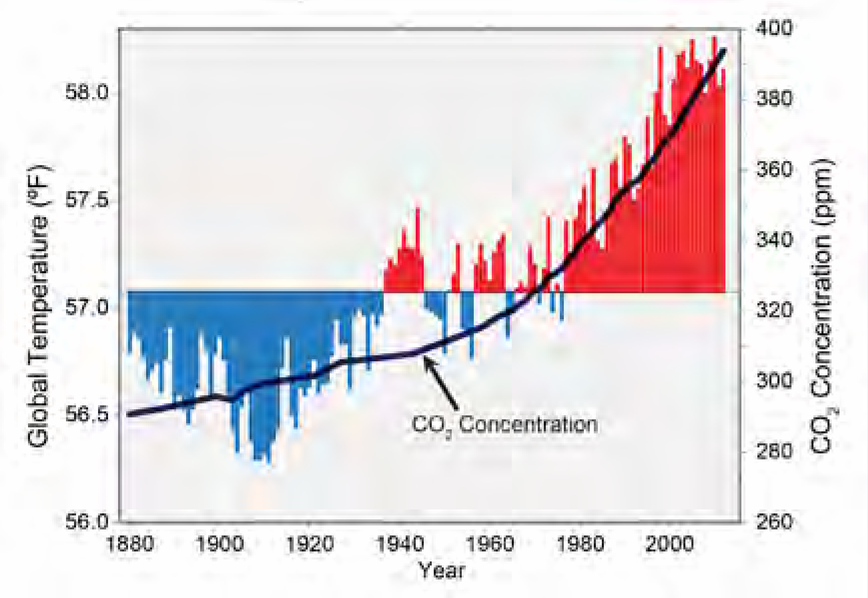

Figure 2.2. Global annual average temperature (as measured over both land and oceans) has increased by more than 1.5°F (0.8°C) since 1880 (through 2012). Red bars show temperatures above the long-term average, and blue bars indicate temperatures below the long-term average. The black line shows atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm). While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are due to natural processes, such as the effects of El Niños, La Niñas, and volcanic eruptions. (Figure source: updated from Karl et al. 2009[1]).

Separating Human and Natural Influences on Climate

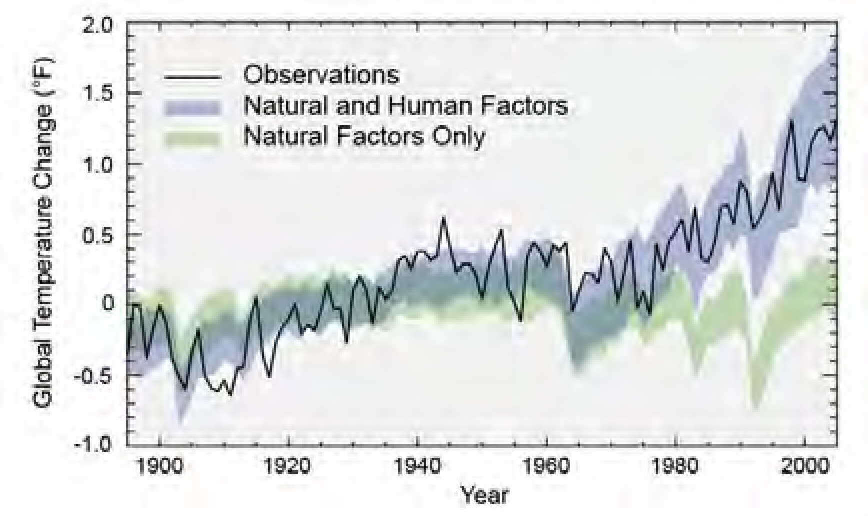

Figure 2.3. Observed global average changes (black line), model simulations using only changes in natural factors (solar and volcanic) in green, and model simulations with the addition of human-induced emissions (blue). Climate changes since 1950 cannot be explained by natural factors or variability, and can only be explained by human factors. (Figure source: adapted from Huber and Knutti[29]).

The third line of evidence comes from using climate models to simulate the climate of the past century, separating the human and natural factors that influence climate. When the human factors are removed, these models show that solar and volcanic activity would have tended to slightly cool the earth, and other natural variations are too small to explain the amount of warming. Only when the human influences are included do the models reproduce the warming observed over the past 50 years (see Figure 2.3).

Another line of evidence involves so-called "fingerprint" studies that are able to attribute observed climate changes to particular causes. For example, the fact that the stratosphere (the layer above the troposphere) is cooling while the Earth's surface and lower atmosphere is warming is a fingerprint that the warming is due to increases in heat-trapping gases. In contrast, if the observed warming had been due to increases in solar output, Earth's atmosphere would have warmed throughout its entire extent, including the stratosphere.[6]

In addition to such temperature analyses, scientific attribution of observed changes to human influence extends to many other aspects of climate, such as changing patterns in precipitation,[12,13] increasing humidity,[14,15] changes in pressure,[16] and increasing ocean heat content.[17] Further discussion of how we know the recent changes in climate are caused by human activity is provided in Appendix 3: Climate Science Supplement.

Natural variations in climate include the effects of cycles such as El Niño, La Niña and other ocean cycles; the 11-year sunspot cycle and other changes in energy from the sun; and the effects of volcanic eruptions. Globally, natural variations can be as large as human-induced climate change over timescales of up to a few decades. However, changes in climate at the global scale observed over the past 50 years are far larger than can be accounted for by natural variability. Changes in climate at the local to regional scale can be influenced by natural variability for multiple decades.[18] This can affect the interpretation of climate trends observed regionally across the U.S. (see Appendix 3: Climate Science Supplement).

Globally averaged surface air temperature has slowed its rate of increase since the late 1990s. This is not in conflict with our basic understanding of global warming and its primary cause. The decade of 2000 to 2009 was still the warmest decade on record. In addition, global surface air temperature does not always increase steadily. This time period is too short to signify a change in the warming trend, as climate trends are measured over periods of decades, not years.[19,20,21,22] Such decade-long slowdowns or even reversals in trend have occurred before in the global instrumental record (for example, 1900-1910 and 1940-1950; see Figure 2.2), including three decade-long periods since 1970, each followed by a sharp temperature rise.[23] Nonetheless, satellite and ocean observations indicate that the Earth-atmosphere climate system has continued to gain heat energy.[24]

There are a number of possible contributions to the lower rate of increase over the last 15 years. First, the solar output during the latest 11-year solar cycle has been lower over the past 15 years than the past 60 years. Second, a series of mildly explosive volcanoes, which increased stratospheric particles, likely had more of a cooling effect than previously recognized.[25] Third, the high incidence of La Niña events in the last 15 years has played a role in the observed trends.[20,26] Recent analyses[27] suggest that more of the increase in heat energy during this period has been transferred to the deep ocean than previously. While this might temporarily slow the rate of increase in surface air temperature, ultimately it will prolong the effects of global warming because the oceans hold heat for longer than the atmosphere does.

Climate models are not intended to match the real-world timing of natural climate variations – instead, models have their own internal timing for such variations. Most modeling studies do not yet account for the observed changes in solar and volcanic forcing mentioned in the previous paragraph. Therefore, it is not surprising that the timing of such a slowdown in the rate of increase in the models would be different than that observed, although it is important to note that such periods *have* been simulated by climate models, with the deep oceans absorbing the extra heat during those decades.[28]


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Oil used for transportation and coal used for electricity generation are the largest contributors to the rise in carbon dioxide that is the primary driver of observed changes in climate over recent decades.

MODELS USED IN THE ASSESSMENT

This report uses various projections from models of the physical processes affecting the Earth's climate system, which are discussed further in Appendix 3: Climate Science Supplement. Three distinct sets of model simulations for past and projected changes in climate are used:

- Coupled Model Intercomparison Project, 3rd phase (CMIP3): global model analyses done for the Fourth Intergovernmental Panel on Climate Change (IPCC) assessment. Spatial resolutions typically vary from 125 to 187 miles (at mid-latitudes); approximately 25 representations of different models (not all are used in all studies). CMIP3 findings are the foundation for most of the impact analyses included in this assessment.
- Coupled Model Intercomparison Project, 5th phase (CMIP5): newer global model analyses done for the Fifth IPCC assessment generally based on improved formulations of the CMIP3 models. Spatial resolutions typically vary from 62 to 125 miles; about 30 representations of different models (not all are used in all studies); this new information was not available in time to serve as the foundation for the impacts analyses in this assessment, and information from CMIP5 is primarily provided for comparison purposes.
- North American Regional Climate Change Assessment Program (NARCCAP): six regional climate model analyses (and limited time-slice analyses from two global models) for the continental U.S. run at about 30-mile horizontal resolution. The analyses were done for past (1971-2000) and projected (2041-2070) time periods. Coarser resolution results from four of the CMIP3 models were used as the boundary conditions for the NARCCAP regional climate model studies, with each of the regional models doing analyses with boundary conditions from two of the CMIP3 models.

The scenarios for future human-related emissions of the relevant gases and particles used in these models are further discussed in Appendix 3: Climate Science Supplement. The emissions in these scenarios depend on various assumptions about changes in global population, economic and technological development, and choices in transportation and energy use.

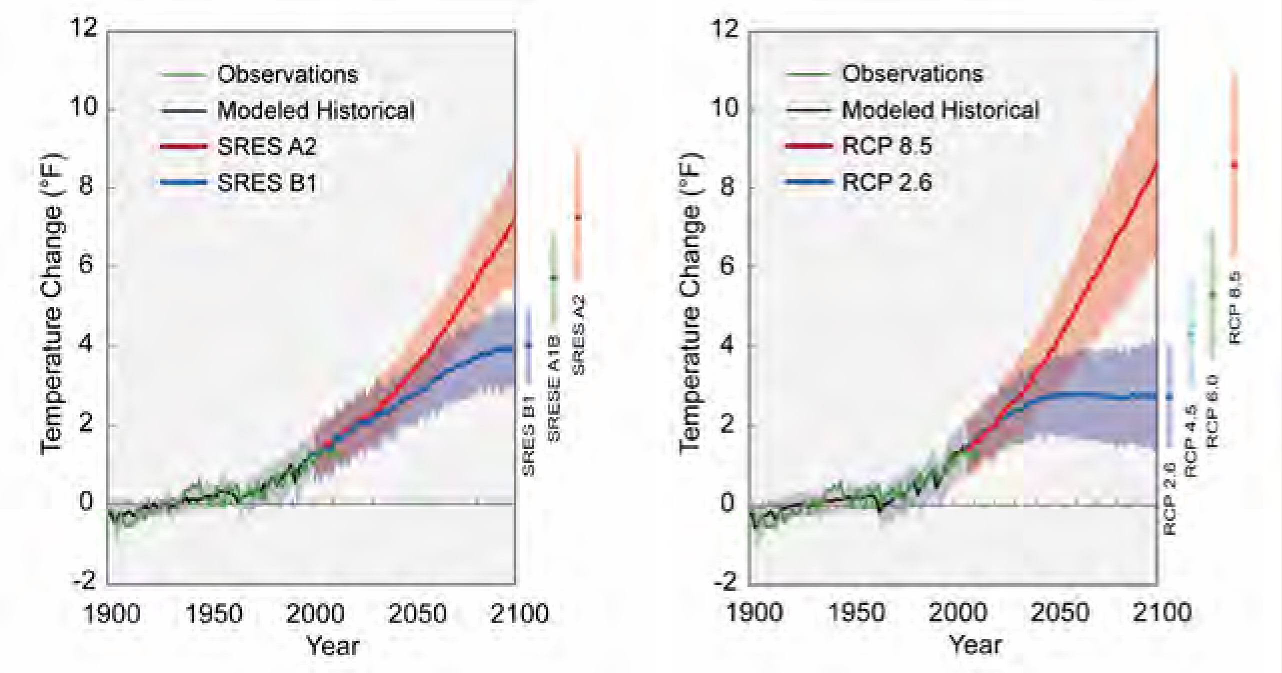
Key Message 2: Future Climate Change

Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.

A certain amount of continued warming of the planet is projected to occur as a result of human-induced emissions to date; another 0.5°F increase would be expected over the next few decades even if all emissions from human activities suddenly stopped,[30] although natural variability could still play an important role over this time period.[31] However, choices made now and in the next few decades will determine the amount of additional future warming. Beyond mid-century, lower levels of heat-trapping gases in scenarios with reduced emissions will lead to noticeably less future warming. Higher emissions levels will result in more warming, and thus more severe impacts on human society and the natural world.

Confidence in projections of future climate change has increased. The wider range of potential changes in global average temperature in the latest generation of climate model simulations[32] used in the Intergovernmental Panel on Climate Change's (IPCC) current assessment – versus those in the previous assessment[8] – is simply a result of considering more options for future human behavior. For example, one of the scenarios included in the IPCC's latest assessment assumes aggressive emissions reductions designed to limit the global temperature increase to 3.6°F (2°C) above pre-industrial levels.[33] This path would require rapid emissions reductions (more than 70% reduction in human-related emissions by 2050, and net negative emissions by 2100 – see the Appendix 3: Climate Science, Supplemental Message 5) sufficient to achieve heat-trapping gas concentrations well below those of any of the scenarios considered by the IPCC in its 2007 assessment. Such scenarios enable the investigation of climate impacts that would be avoided by deliberate, substantial reductions in heat-trapping gas emissions.

Projections of future changes in precipitation show small increases in the global average but substantial shifts in where and how precipitation falls. Generally, areas closest to the poles are projected to receive more precipitation, while the dry subtropics (the region just outside the tropics, between 23° and 35° on either side of the equator) expand toward the poles and receive less rain. Increases in tropical precipitation are projected during rainy seasons (such as monsoons), especially over the tropical Pacific. Certain regions, including the western U.S. (especially the Southwest[1]) and the Mediterranean, are presently dry and are expected to become drier. The widespread trend of increasing heavy downpours is expected to continue, with precipitation becoming less frequent but more intense.[34] The patterns of the projected changes of precipitation do not contain the spatial details that characterize observed precipitation, especially in mountainous terrain, because the projections are averages from multiple models and because the effective resolution of global climate models is roughly 100-200 miles.



Emissions Levels Determine Temperature Rises

Figure 2.4. Different amounts of heat-trapping gases released into the atmosphere by human activities produce different projected increases in Earth's temperature. In the figure, each line represents a central estimate of global average temperature rise (relative to the 1901-1960 average) for a specific emissions pathway. Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. Projections in 2099 for additional emissions pathways are indicated by the bars to the right of each panel. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. **(Left)** The panel shows the two main scenarios (SRES – Special Report on Emissions Scenarios) used in this report: A2 assumes continued increases in emissions throughout this century, and B1 assumes much slower increases in emissions beginning now and significant emissions reductions beginning around 2050, though not due explicitly to climate change policies. **(Right)** The panel shows newer analyses, which are results from the most recent generation of climate models (CMIP5) using the most recent emissions pathways (RCPs – Representative Concentration Pathways). Some of these new projections explicitly consider climate policies that would result in emissions reductions, which the SRES set did not.[35] The newest set includes both lower and higher pathways than did the previous set. The lowest emissions pathway shown here, RCP 2.6, assumes immediate and rapid reductions in emissions and would result in about 2.5°F of warming in this century. The highest pathway, RCP 8.5, roughly similar to a continuation of the current path of global emissions increases, is projected to lead to more than 8°F warming by 2100, with a high-end possibility of more than 11°F. (Data from CMIP3, CMIP5, and NOAA NCDC).

Projected Change in Average Annual Temperature

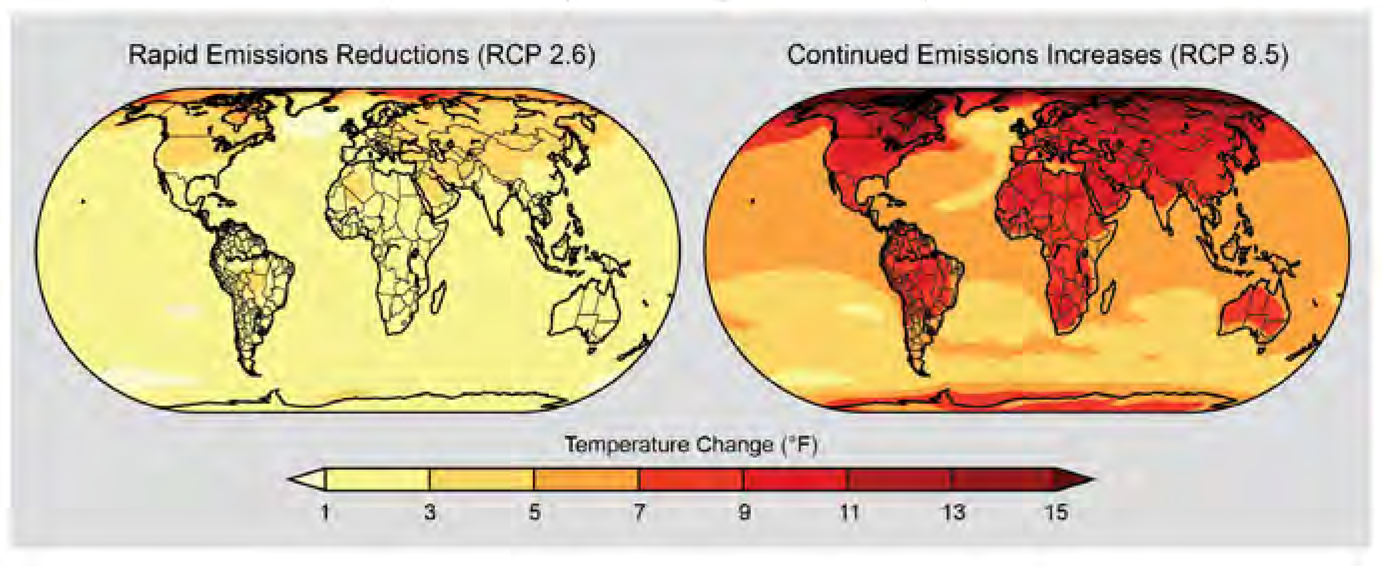


Figure 2.5. Projected change in average annual temperature over the period 2071-2099 (compared to the period 1970-1999) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gases (RCP 2.6), and a higher scenario that assumes continued increases in emissions (RCP 8.5). (Figure source: NOAA NCDC / CICS-NC).

Projected Change in Average Annual Precipitation

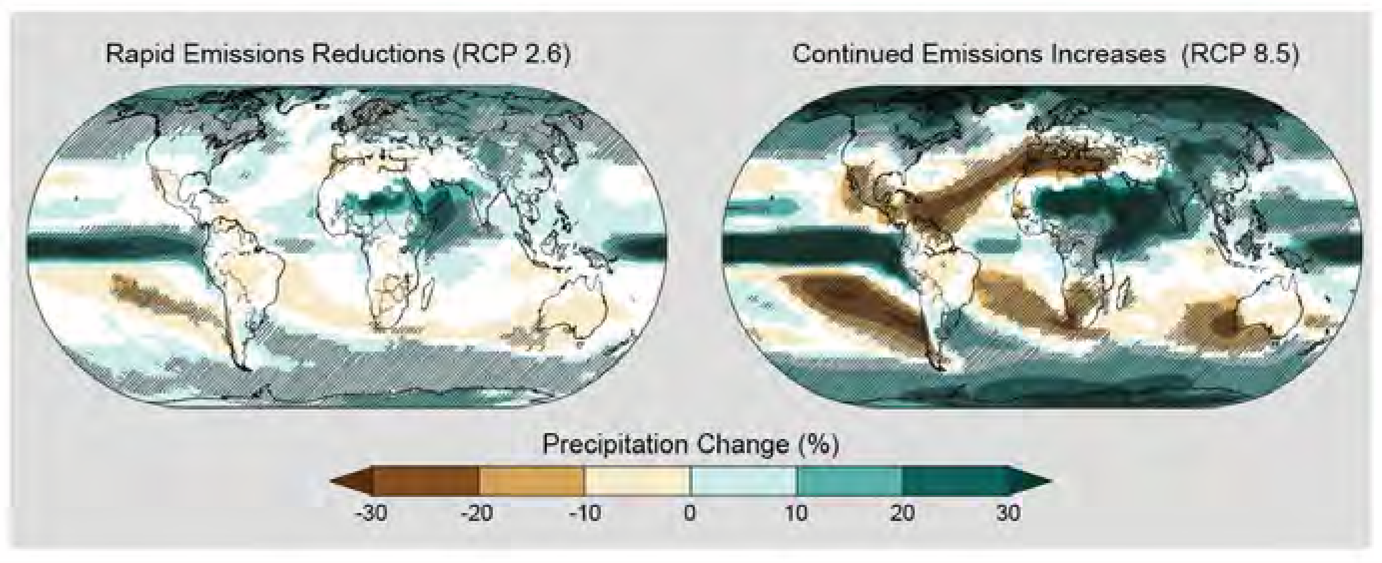


Figure 2.6. Projected change in average annual precipitation over the period 2071-2099 (compared to the period 1970-1999) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gasses (RCP 2.6), and a higher scenario that assumes continued increases in emissions (RCP 8.5). Hatched areas indicate confidence that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In general, northern parts of the U.S. (especially the Northeast and Alaska) are projected to receive more precipitation, while southern parts (especially the Southwest) are projected to receive less. (Figure source: NOAA NCDC / CICS-NC).

CLIMATE SENSITIVITY

"Climate sensitivity" is an important concept because it helps us estimate how much warming might be expected for a given increase in the amount of heat-trapping gases. It is defined as the amount of warming expected if carbon dioxide (CO_2) concentrations doubled from pre-industrial levels and then remained constant until Earth's temperature reached a new equilibrium over timescales of centuries to millennia. Climate sensitivity accounts for feedbacks in the climate system that can either dampen or amplify warming. The feedbacks primarily determining that response are related to water vapor, ice and snow reflectivity, and clouds.[8] Cloud feedbacks have the largest uncertainty. The net effect of these feedbacks is expected to amplify warming.[8]

Climate sensitivity has long been estimated to be in the range of 2.7°F to 8.1°F. As discussed in Appendix 3: Climate Science Supplement, recent evidence lends further confidence in this range.

One important determinant of how much climate will change is the effect of so-called "feedbacks" in the climate system, which can either dampen or amplify the initial effect of human influences on temperature. One important climate feedback is the loss of summer Arctic sea ice, allowing absorption of substantially more of the sun's heat in the Arctic, increasing warming, and possibly causing changes in weather patterns over the United States.

The observed drastic reduction in sea ice can also lead to a "tipping point" – a point beyond which an abrupt or irreversible transition to a different climatic state occurs. In this case, the dramatic loss of sea ice could tip the Arctic Ocean into a permanent, nearly ice-free state in summer, with repercussions that may extend far beyond the Arctic. Such potential "tipping points" have been identified in various components of the Earth's climate system and could have important effects on future climate. The extent and magnitude of these potential effects are still unknown. These are discussed further in the Appendix 4: Frequently Asked Questions, under Question T.

Key Message 3: Recent U.S. Temperature Trends

U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the nation's warmest on record. Temperatures in the United States are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

There have been substantial advances in our understanding of the U.S. temperature record since the 2009 assessment (see Appendix 3: Climate Science, Supplemental Message 7 for more information). These advances confirm that the U.S. annually averaged temperature has increased by 1.3°F to 1.9°F since 1895.[1,36,37,38] However, this increase was not constant over time. In particular, temperatures generally rose until about 1940, declined slightly until about 1970, then increased rapidly thereafter. The year 2012 was the warmest on record for the contiguous United States. Over shorter time scales (one to two decades), natural variability can reduce the rate of warming or even create a temporary cooling (see Appendix 3: Climate Science, Supplemental Message 3). The cooling in mid-century that was especially prevalent over the eastern half of the U.S. may have stemmed partly from such natural variations and partly from human influences, in particular the cooling effects of sulfate particles from coal-burning power plants,[39] before these sulfur emissions were regulated to address health and acid rain concerns.

QUANTIFYING U.S. TEMPERATURE RISE

Quantifying long-term increases of temperature in the U.S. in a single number is challenging because the increase has not been constant over time. The increase can be quantified in a number of ways, but all of them show significant warming over the U.S. since the instrumental record began in 1895. For example, fitting a linear trend over the period 1895 to 2012 yields an increase in the range of 1.3 to 1.9°F. Another approach, comparing the average temperature during the first decade of record with the average during the last decade of record, yields a 1.9°F increase. A third approach, calculating the difference between the 1901-1960 average and the past decade average yields a change of 1.5°F. Thus, the temperature increase cited in this assessment is described as 1.3°F to 1.9°F since 1895. Notably, however, the rate of rise in temperature over the past 4 to 5 decades has been greater than the rate over earlier decades.

Observed U.S. Temperature Change

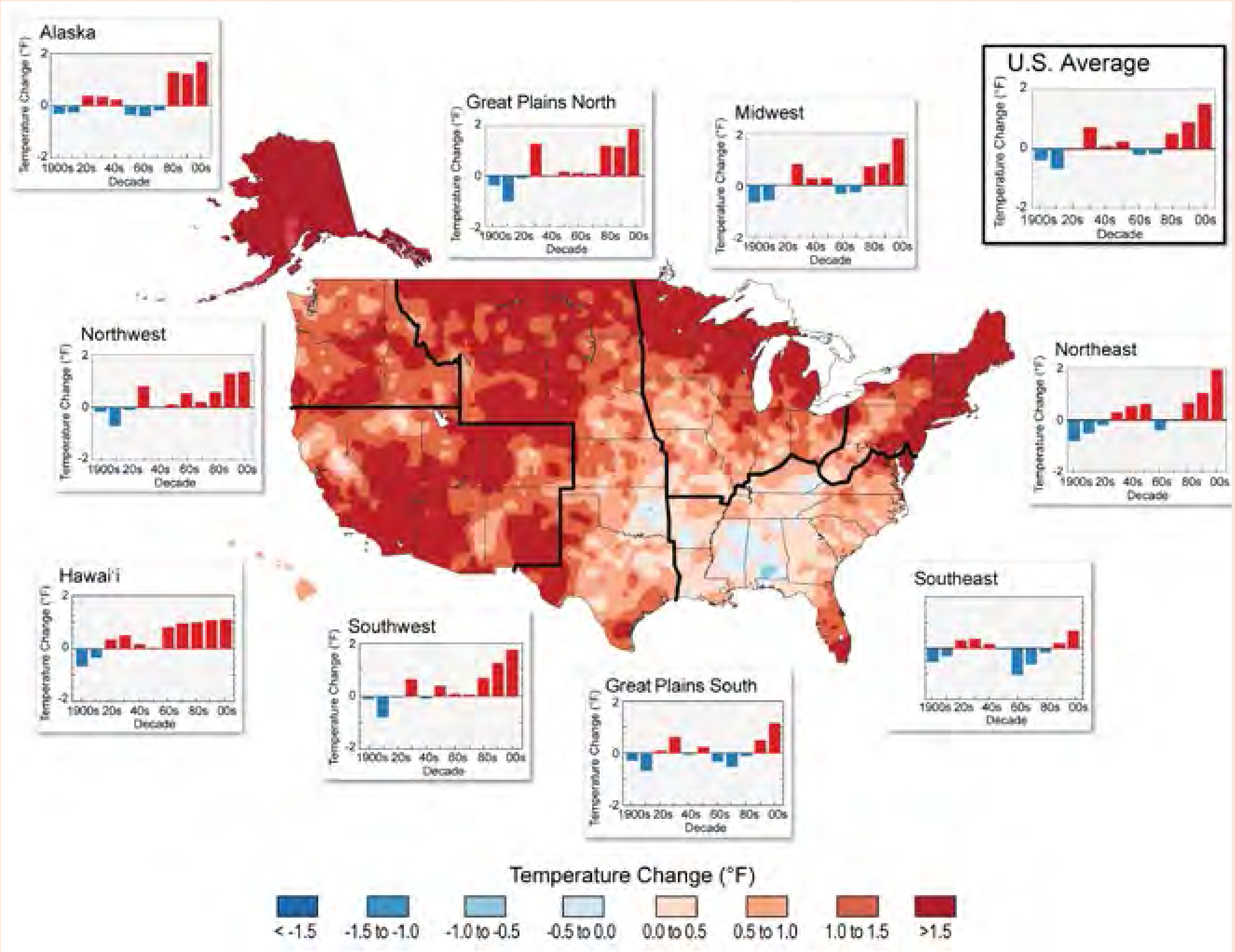


Figure 2.7. The colors on the map show temperature changes over the past 22 years (1991-2012) compared to the 1901-1960 average, and compared to the 1951-1980 average for Alaska and Hawai'i. The bars on the graphs show the average temperature changes by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 was warmer than any previous decade in every region. (Figure source: NOAA NCDC / CICS-NC).

Since 1991, temperatures have averaged 1°F to 1.5°F higher than 1901-1960 over most of the United States, except for the Southeast, where the warming has been less than 1°F. On a seasonal basis, long-term warming has been greatest in winter and spring.

Warming is ultimately projected for all parts of the nation during this century. In the next few decades, this warming will be roughly 2°F to 4°F in most areas. By the end of the century, U.S. warming is projected to correspond closely to the level of global emissions: roughly 3°F to 5°F under lower emissions scenarios (B1 or RCP 4.5) involving substantial reductions in emissions, and 5°F to 10°F for higher emissions scenarios (A2 or RCP 8.5) that assume continued increases in emissions; the largest temperature increases are projected for the upper Midwest and Alaska.

Future human-induced warming depends on both past and future emissions of heat-trapping gases and changes in the amount of particle pollution. The amount of climate change (aside from natural variability) expected for the next two to three decades is a combination of the warming already built into the climate system by the past history of human emissions of heat-trapping gases, and the expected ongoing increases in emissions of those gases. However, the magnitude of temperature increases over the second half of this century, both in the U.S. and globally, will be primarily determined by the emissions produced now and over the next few decades, and there are substantial differences between higher, fossil-fuel intensive scenarios compared to scenarios in which emissions are reduced. The most recent model projections of climate change due to human activities expand the range of future scenarios considered (particularly at the lower end), but are entirely consistent with the older model results. This consistency increases our confidence in the projections.

Projected Temperature Change

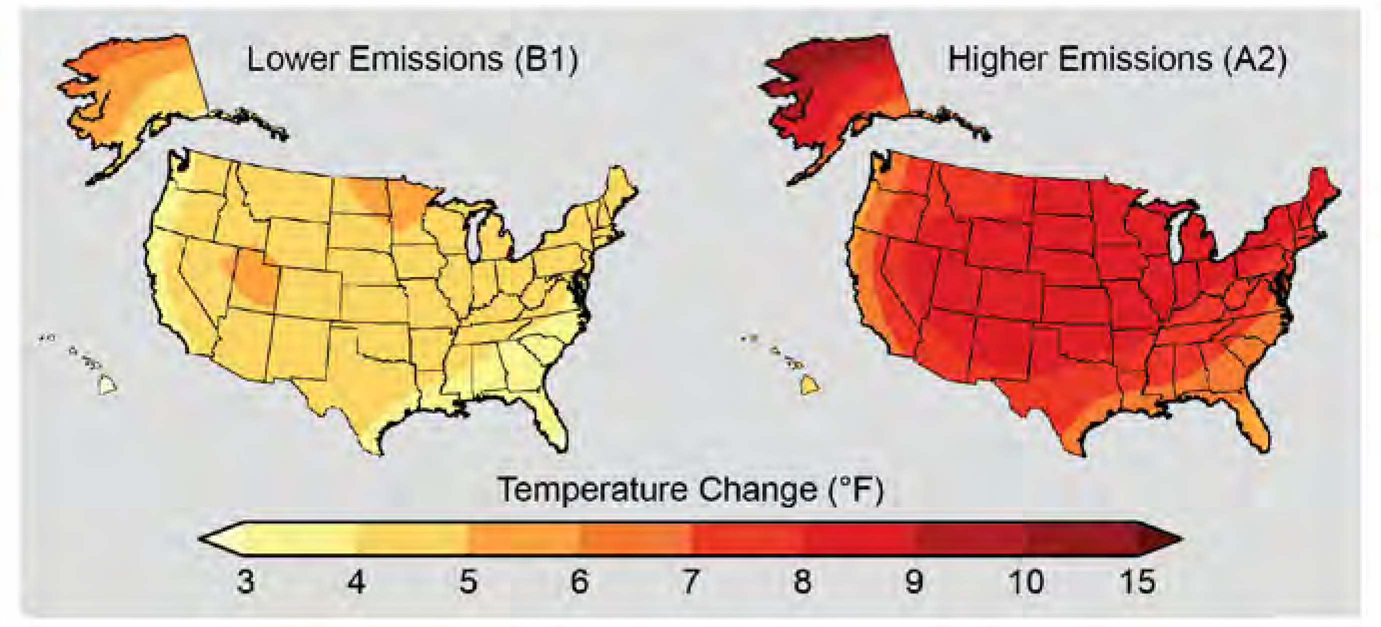


Figure 2.8. Maps show projected change in average surface air temperature in the later part of this century (2071-2099) relative to the later part of the last century (1970-1999) under a scenario that assumes substantial reductions in heat trapping gases (B1, left) and a higher emissions scenario that assumes continued increases in global emissions (A2, right). (See Appendix 3: Climate Science, Supplemental Message 5 for a discussion of temperature changes under a wider range of future scenarios for various periods of this century). (Figure source: NOAA NCDC / CICS-NC).

NEWER SIMULATIONS FOR PROJECTED TEMPERATURE (CMIP5 MODELS)

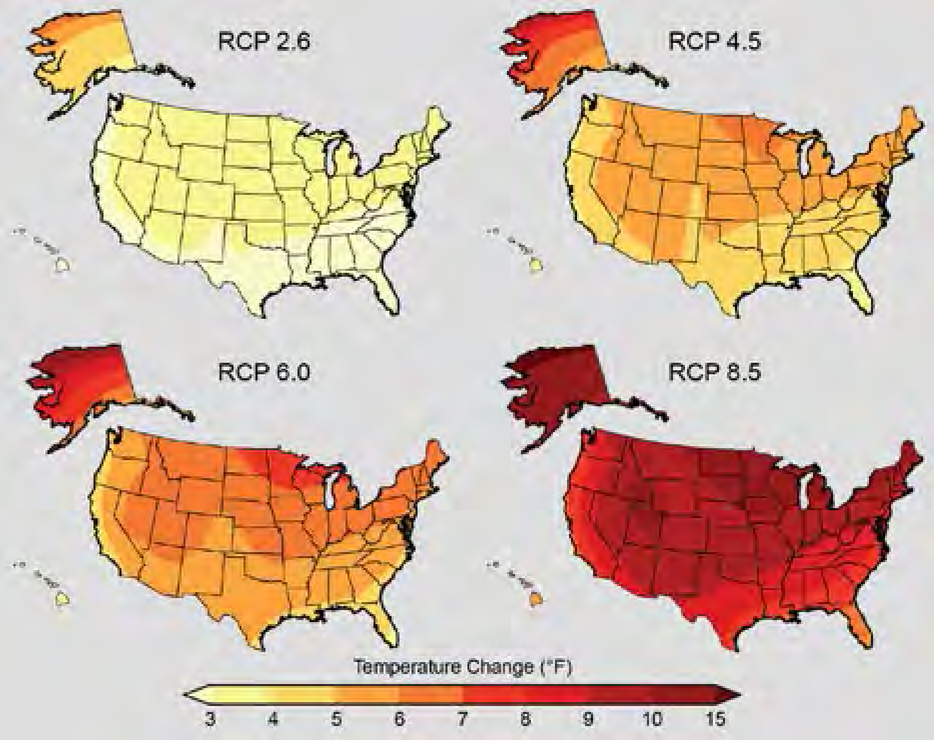


Figure 2.9. The largest uncertainty in projecting climate change beyond the next few decades is the level of heat-trapping gas emissions. The most recent model projections (CMIP5) take into account a wider range of options with regard to human behavior, including a lower scenario than has been considered before (RCP 2.6). This scenario assumes rapid reductions in emissions – more than 70% cuts from current levels by 2050 and further large decreases by 2100 – and the corresponding smaller amount of warming. On the higher end, the scenarios include one that assumes continued increases in emissions (RCP 8.5) and the corresponding greater amount of warming. Also shown are temperature changes for the intermediate scenarios RCP 4.5 (which is most similar to B1) and RCP 6.0 (which is most similar to A1B; see Appendix 3: Climate Science Supplement). Projections show change in average temperature in the later part of this century (2071-2099) relative to the late part of last century (1970-1999). (Figure source: NOAA NCDC / CICS-NC).

Key Message 4: Lengthening Frost-free Season

The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.

The length of the frost-free season (and the corresponding growing season) is a major determinant of the types of plants and crops that do well in a particular region. The frost-free season length has been gradually increasing since the 1980s.[40] The last occurrence of 32°F in the spring has been occurring earlier in the year, and the first occurrence of 32°F in the fall has been happening later. During 1991-2011, the average frost-free season was about 10 days longer than during 1901-1960. These observed climate changes have been mirrored by changes in the biosphere, including increases in forest productivity[41,42] and satellite-derived estimates of the length of the growing season.[43] A longer growing season provides a longer period for plant growth and productivity and can slow the increase in atmospheric CO_2 concentrations through increased CO_2 uptake by living things and their environment.[44] The longer growing season can increase the growth of beneficial plants (such as crops and forests) as well as undesirable ones (such as ragweed).[45] In some cases where moisture is limited, the greater evaporation and loss of moisture through plant transpiration (release of water from plant leaves) associated with a longer growing season can mean less productivity because of increased drying[46] and earlier and longer fire seasons.

Observed Increase in Frost-Free Season Length

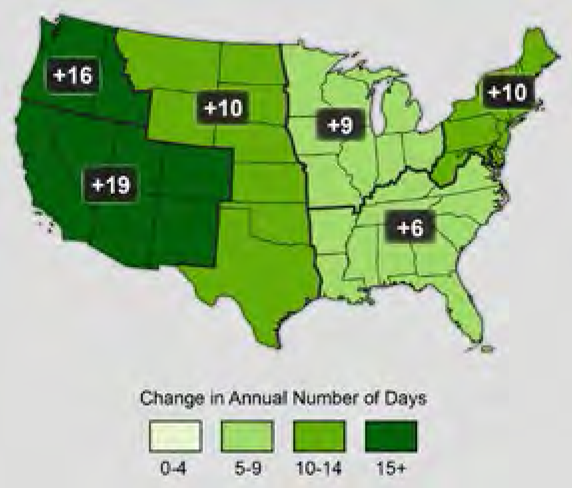


Figure 2.10. The frost-free season length, defined as the period between the last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall, has increased in each U.S. region during 1991-2012 relative to 1901-1960. Increases in frost-free season length correspond to similar increases in growing season length. (Figure source: NOAA NCDC / CICS-NC).

The lengthening of the frost-free season has been somewhat greater in the western U.S. than the eastern United States,[1] increasing by 2 to 3 weeks in the Northwest and Southwest, 1 to 2 weeks in the Midwest, Great Plains, and Northeast, and slightly less than 1 week in the Southeast. These differences mirror the overall trend of more warming in the north and west and less warming in the Southeast.

Projected Changes in Frost-Free Season Length

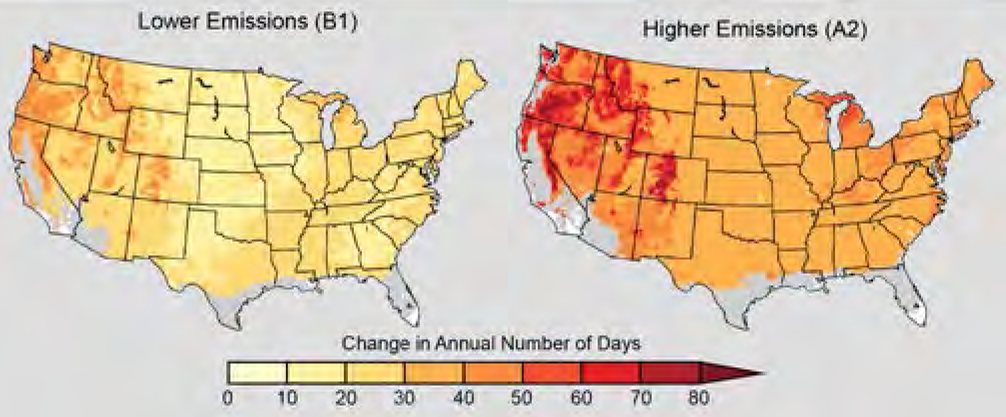


Figure 2.11. The maps show projected increases in frost-free season length for the last three decades of this century (2070-2099 as compared to 1971-2000) under two emissions scenarios, one in which heat-trapping gas emissions continue to grow (A2) and one in which emissions peak in 2050 (B1). Increases in the frost-free season correspond to similar increases in the growing season. White areas are projected to experience no freezes for 2070-2099, and gray areas are projected to experience more than 10 frost-free years during the same period. (Figure source: NOAA NCDC / CICS-NC).

In a future in which heat-trapping gas emissions continue to grow, increases of a month or more in the lengths of the frost-free and growing seasons are projected across most of the U.S. by the end of the century, with slightly smaller increases in the northern Great Plains. The largest increases in the frost-free season (more than 8 weeks) are projected for the western U.S., particularly in high elevation and coastal areas. The increases will be considerably smaller if heat-trapping gas emissions are reduced, although still substantial. These increases are projected to be much greater than the normal year-to-year variability experienced today. The projected changes also imply that the southern boundary of the seasonal freeze zone will move northward, with increasing frequencies of years without subfreezing temperatures in the most southern parts of the United States.

Key Message 5: U.S. Precipitation Change

Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.

Since 1900, average annual precipitation over the U.S. has increased by roughly 5%. This increase reflects, in part, the major droughts of the 1930s and 1950s, which made the early half of the record drier. There are important regional differences. For instance, precipitation since 1991 (relative to 1901-1960) increased the most in the Northeast (8%), Midwest (9%), and southern Great Plains (8%), while much of the Southeast and Southwest had a mix of areas of increases and decreases.[47,48]

While significant trends in average precipitation have been detected, the fraction of these trends attributable to human activity is difficult to quantify at regional scales because the range of natural variability in precipitation is large. Projected changes are generally small for central portions of the United States. However, if emissions of heat-trapping gases continue their upward trend, certain global patterns of precipitation change are projected to emerge that will affect northern and

Observed U.S. Precipitation Change

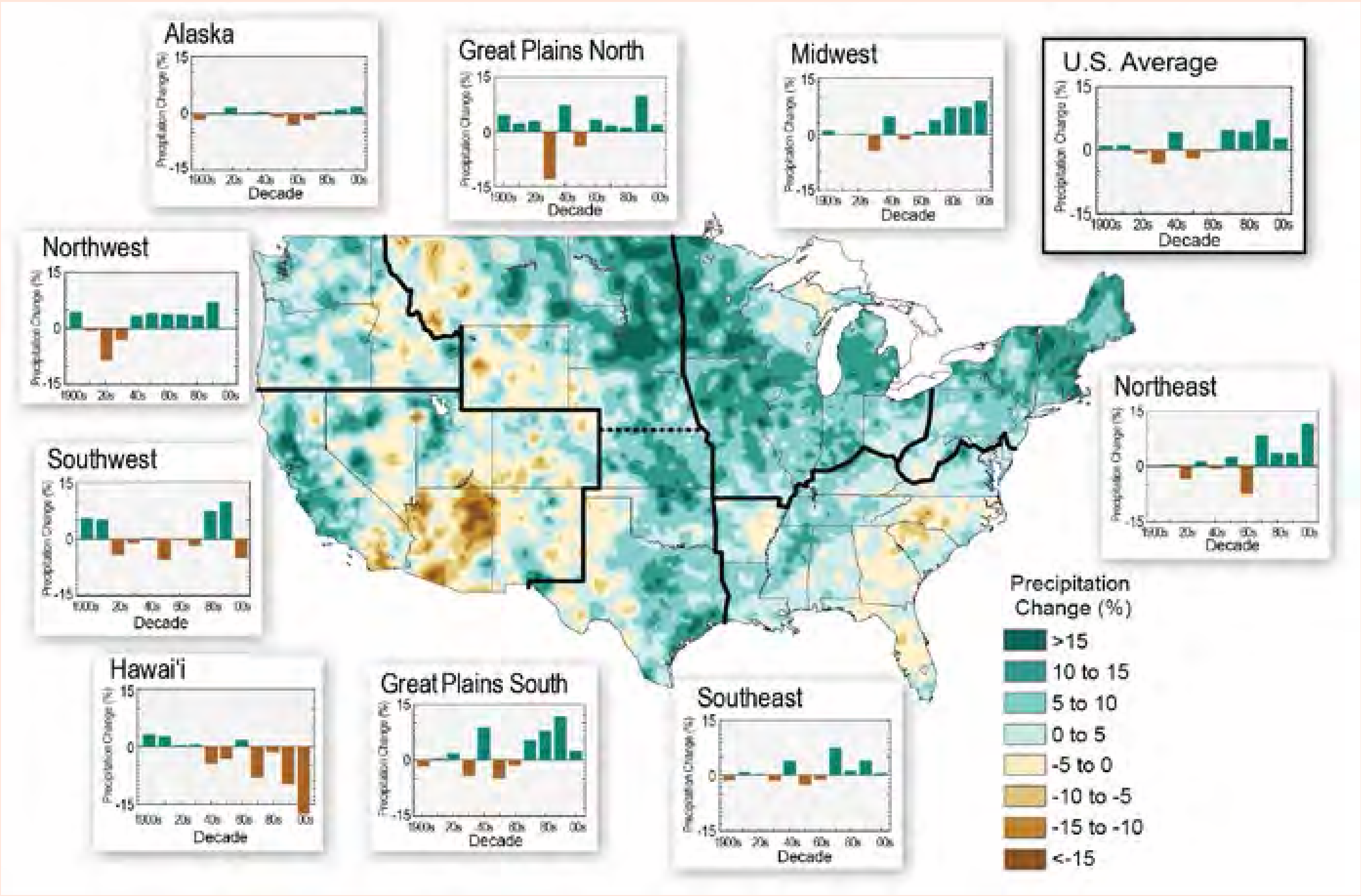


Figure 2.12. The colors on the map show annual total precipitation changes for 1991-2012 compared to the 1901-1960 average, and show wetter conditions in most areas. The bars on the graphs show average precipitation differences by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph is for 2001-2012. (Figure source: adapted from Peterson et al. 2013[48]).

southwestern areas of the United States. The northern U.S. is projected to experience more precipitation in the winter and spring (except for the Northwest in the spring), while the Southwest is projected to experience less, particularly in the spring. The contrast between wet and dry areas will increase both in the U.S. and globally – in other words, the wet areas will get wetter and the dry areas will get drier. As discussed in the next section, there has been an increase in the amount of precipitation falling in heavy events[49] and this is projected to continue.

The projected changes in the northern U.S. are a consequence of both a warmer atmosphere (which can hold more moisture than a colder one) and associated changes in large-scale

UNCERTAINTIES IN REGIONAL PROJECTIONS

On the global scale, climate model simulations show consistent projections of future conditions under a range of emissions scenarios. For temperature, all models show warming by late this century that is much larger than historical variations nearly everywhere. For precipitation, models are in complete agreement in showing decreases in precipitation in the subtropics and increases in precipitation at higher latitudes.

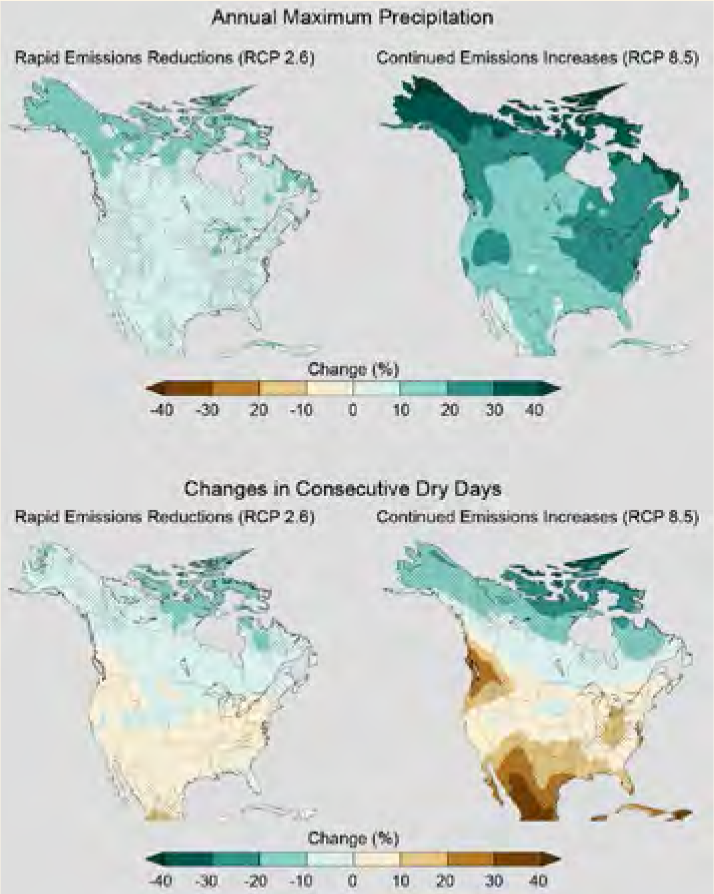


Figure 2.13. Top panels show simulated changes in the average amount of precipitation falling on the wettest day of the year for the period 2070-2099 as compared to 1971-2000 under a scenario that assumes rapid reductions in emissions (RCP 2.6) and one that assumes continued emissions increases (RCP 8.5). Bottom panels show simulated changes in the annual maximum number of consecutive dry days (days receiving less than 0.04 inches (1 mm) of precipitation) under the same two scenarios. Simulations are from CMIP5 models. Stippling indicates areas where changes are consistent among at least 80% of the models used in this analysis. (Figure source: NOAA NCDC / CICS-NC).

Models unequivocally project large and historically unprecedented future warming in every region of the U.S. under all of the scenarios used in this assessment. The amount of warming varies substantially between higher versus lower scenarios, and moderately from model to model, but the amount of projected warming is larger than the model-to-model range.

The contiguous U.S. straddles the transition zone between drier conditions in the sub-tropics (south) and wetter conditions at higher latitudes (north). Because the precise location of this zone varies somewhat among models, projected changes in precipitation in central areas of the U.S. range from small increases to small decreases. A clear direction of change only occurs in Alaska and the far north of the contiguous U.S. where increases are projected and in the far Southwest where decreases are projected.

Although this means that changes in overall precipitation are uncertain in many U.S. areas, there is a high degree of certainty that the heaviest precipitation events will increase everywhere, and by large amounts (Figure 2.13). This consistent model projection is well understood and is a direct outcome of the increase in atmospheric moisture caused by warming. There is also more certainty regarding dry spells. The annual maximum number of consecutive dry days is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States. Thus, both extreme wetness and extreme dryness are projected to increase in many areas.

Modeling methods that downscale (generate higher spatial resolution) climate projections from coarser global model output can reduce the range of projections to the extent that they incorporate better representation of certain physical processes (such as the influence of topography and convection). However, a sizeable portion of the range is a result of the variations in large-scale patterns produced by the global models and so downscaling methods do not change this.

weather patterns (which affect where precipitation occurs). The projected reduction in Southwest precipitation is a result of changes in large-scale weather patterns, including the northward expansion of the belt of high pressure in the subtropics, which suppresses rainfall. Recent improvements in understanding these mechanisms of change increase confidence in these projections.[50] The patterns of the projected changes of precipitation resulting from human alterations of the climate are geographically smoother in these maps than what will actually be observed because: 1) the precise locations of natural increases and decreases differ from model to model, and averaging across models smooths these differences; and 2) the resolution of current climate models is too coarse to capture fine topographic details, especially in mountainous terrain. Hence, there is considerably more confidence in the large-scale patterns of change than in local details.

In general, a comparison of the various sources of climate model data used in this assessment provides a consistent picture of the large-scale projected precipitation changes

Projected Precipitation Change by Season

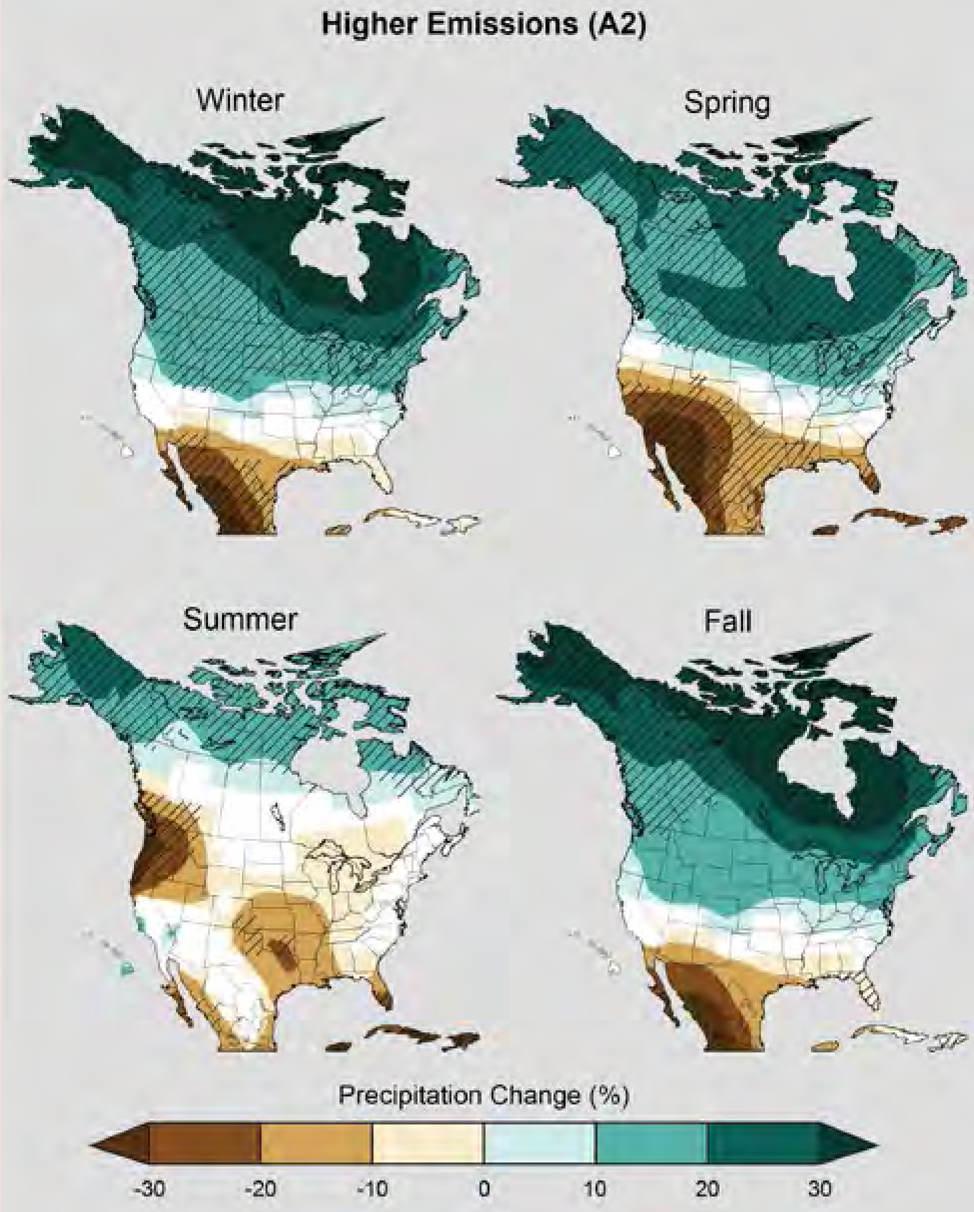


Figure 2.14. Projected change in seasonal precipitation for 2071-2099 (compared to 1970-1999) under an emissions scenario that assumes continued increases in emissions (A2). Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In general, the northern part of the U.S. is projected to see more winter and spring precipitation, while the southwestern U.S. is projected to experience less precipitation in the spring. (Figure source: NOAA NCDC / CICS-NC).

across the United States (see "Models Used in the Assessment"). Multi-model average changes in all three of these sources show a general pattern of wetter future conditions in the north and drier conditions in the south. The regional suite generally shows conditions that are somewhat wetter overall in the wet areas and not as dry in the dry areas. The general pattern agreement among these three sources, with the wide variations in their spatial resolution, provides confidence that this pattern is robust and not sensitive to the limited spatial resolution of the models. The slightly different conditions in the North American NARCCAP regional analyses for the U.S. appear to arise partially or wholly from the choice of the four CMIP3 global climate models used to drive the regional simulations. These four global models, averaged together, project average changes that are 2% wetter than the average of the suite of global models used in CMIP3.

The patterns of precipitation change in the newer CMIP5 simulations are essentially the same as in the earlier CMIP3 and NARCCAP simulations used in impact analyses throughout this report, increasing confidence in our scientific understanding. The subtle differences between these two sets of projections are mostly due to the wider range of future scenarios considered in the more recent simulations. Thus, the overall picture remains the same: wetter conditions in the north and drier conditions in the Southwest in winter and spring. Drier conditions are projected for summer in most areas of the contiguous U.S. but, outside of the Northwest and south-central region, there is generally not high confidence that the changes will be large compared to natural variability. In all models and scenarios, a transition zone between drier (to the south) and wetter (to the north) shifts northward from the southern U.S. in winter to southern Canada in summer. Wetter conditions are projected for Alaska and northern Canada in all seasons.

NEWER SIMULATIONS FOR PROJECTED PRECIPITATION CHANGE (CMIP5 MODELS)

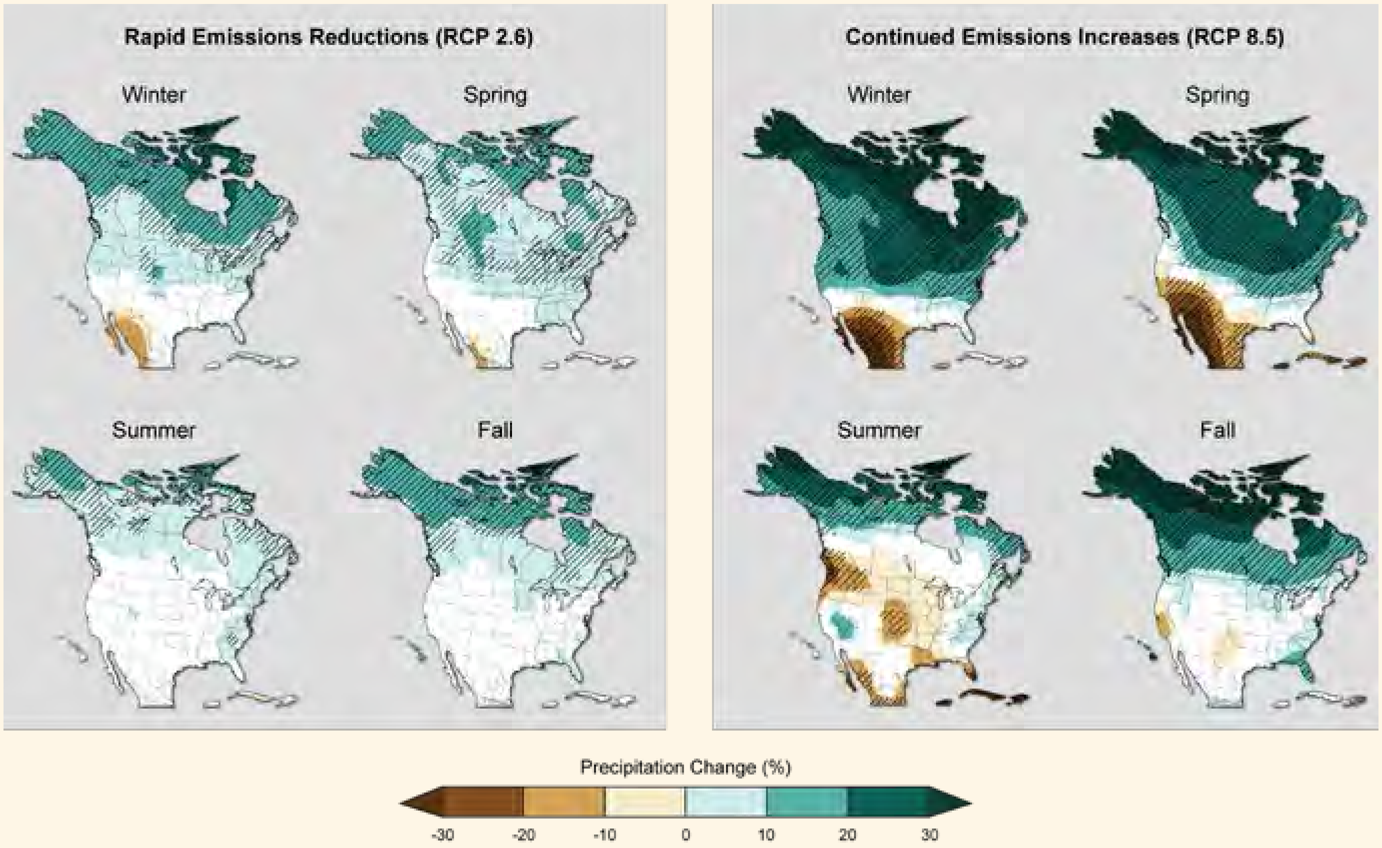


Figure 2.15. Seasonal precipitation change for 2071-2099 (compared to 1970-1999) as projected by recent simulations that include a wider range of scenarios. The maps on the left (RCP 2.6) assume rapid reductions in emissions – more than 70% cuts from current levels by 2050 – and a corresponding much smaller amount of warming and far less precipitation change. On the right, RCP 8.5 assumes continued increases in emissions, with associated large increases in warming and major precipitation changes. These would include, for example, large reductions in spring precipitation in the Southwest and large increases in the Northeast and Midwest. Rapid emissions reductions would be required for the more modest changes in the maps on the left. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. (Figure source: NOAA NCDC / CICS-NC).

Key Message 6: Heavy Downpours Increasing

Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.

Across most of the United States, the heaviest rainfall events have become heavier and more frequent. The amount of rain falling on the heaviest rain days has also increased over the past few decades. Since 1991, the amount of rain falling in very heavy precipitation events has been significantly above average. This increase has been greatest in the Northeast, Midwest, and upper Great Plains – more than 30% above the 1901-1960 average (see Figure 2.18). There has also been an increase in flooding events in the Midwest and Northeast where the largest increases in heavy rain amounts have occurred.

Observed U.S. Trend in Heavy Precipitation

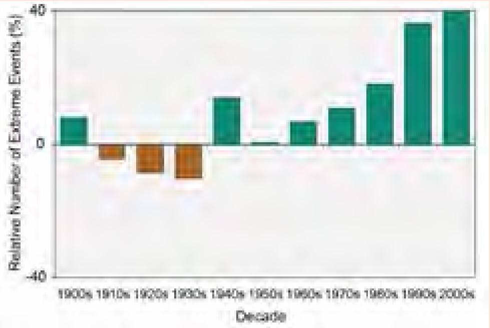


Figure 2.16: One measure of a heavy precipitation event is a 2-day precipitation total that is exceeded on average only once in a five-year period, also known as a once-in-five-year event. As this extreme precipitation index for 1901-2012 shows, the occurrence of such events has become much more common in recent decades. Changes are compared to the period 1901-1960, and do not include Alaska or Hawai'i. The 2000s decade (far right bar) includes 2001-2012. (Figure source: adapted from Kunkel et al. 2013[52]).

Observed Change in Very Heavy Precipitation

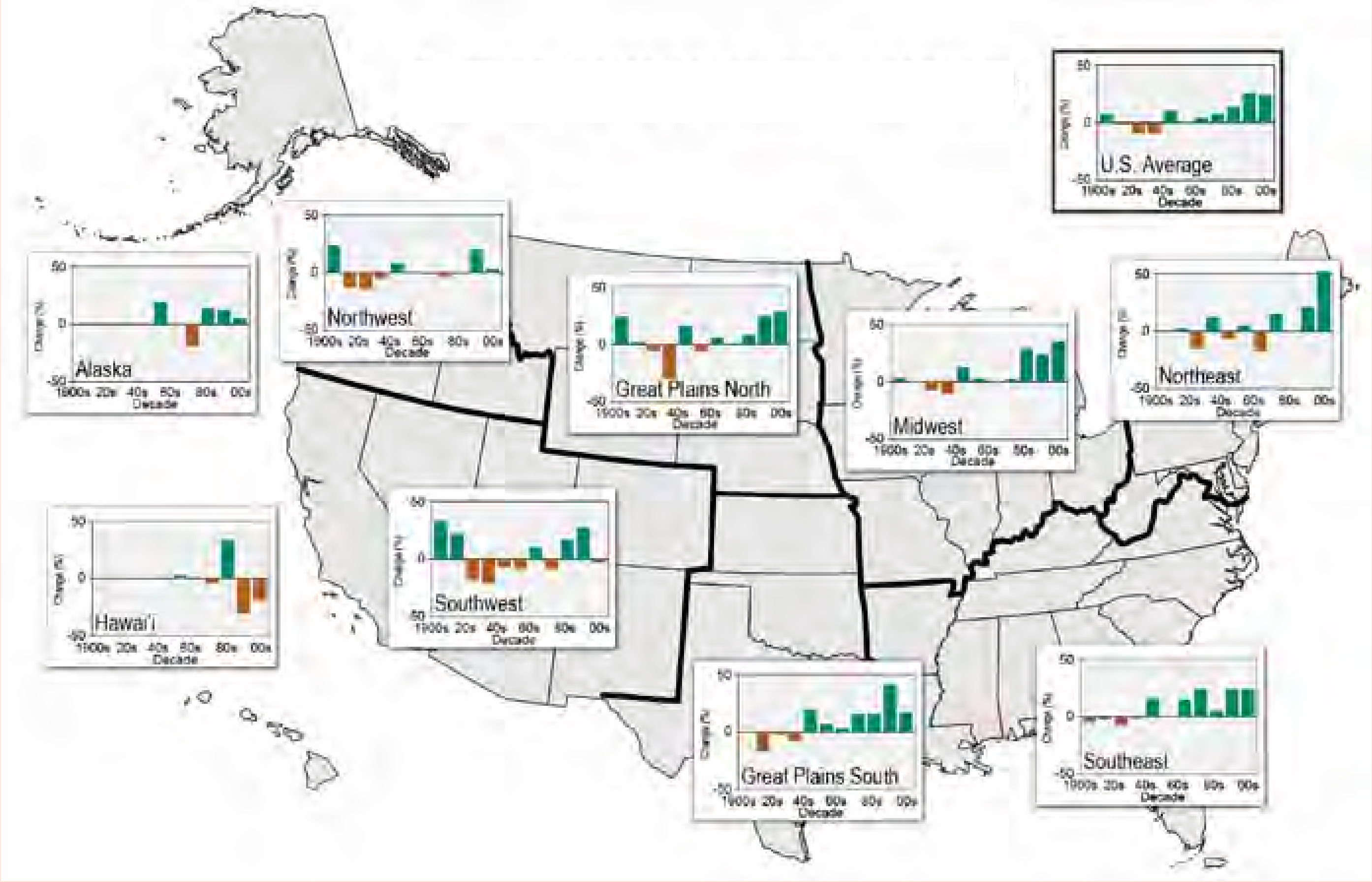


Figure 2.17. Percent changes in the annual amount of precipitation falling in very heavy events, defined as the heaviest 1% of all daily events from 1901 to 2012 for each region. The far right bar is for 2001-2012. In recent decades there have been increases nationally, with the largest increases in the Northeast, Great Plains, Midwest, and Southeast. Changes are compared to the 1901-1960 average for all regions except Alaska and Hawai'i, which are relative to the 1951-1980 average. (Figure source: NOAA NCDC / CICS-NC).

Warmer air can contain more water vapor than cooler air. Global analyses show that the amount of water vapor in the atmosphere has in fact increased over both land and oceans.[14,51] Climate change also alters dynamical characteristics of the atmosphere that in turn affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an upward trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms.[52] Locally, natural variations can also be important.[53]

Projections of future climate over the U.S. suggest that the recent trend towards increased heavy precipitation events will continue. This is projected to occur even in regions where total precipitation is projected to decrease, such as the Southwest.[52,54,55]

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Observed Change in Very Heavy Precipitation

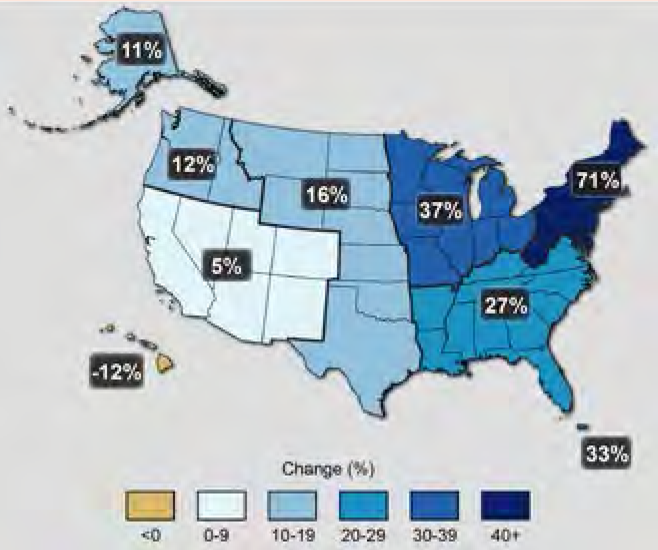

Figure 2.18. The map shows percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental United States. These trends are larger than natural variations for the Northeast, Midwest, Puerto Rico, Southeast, Great Plains, and Alaska. The trends are not larger than natural variations for the Southwest, Hawai'i, and the Northwest. The changes shown in this figure are calculated from the beginning and end points of the trends for 1958 to 2012. (Figure source: updated from Karl et al. 2009[1]).

Projected Change in Heavy Precipitation Events

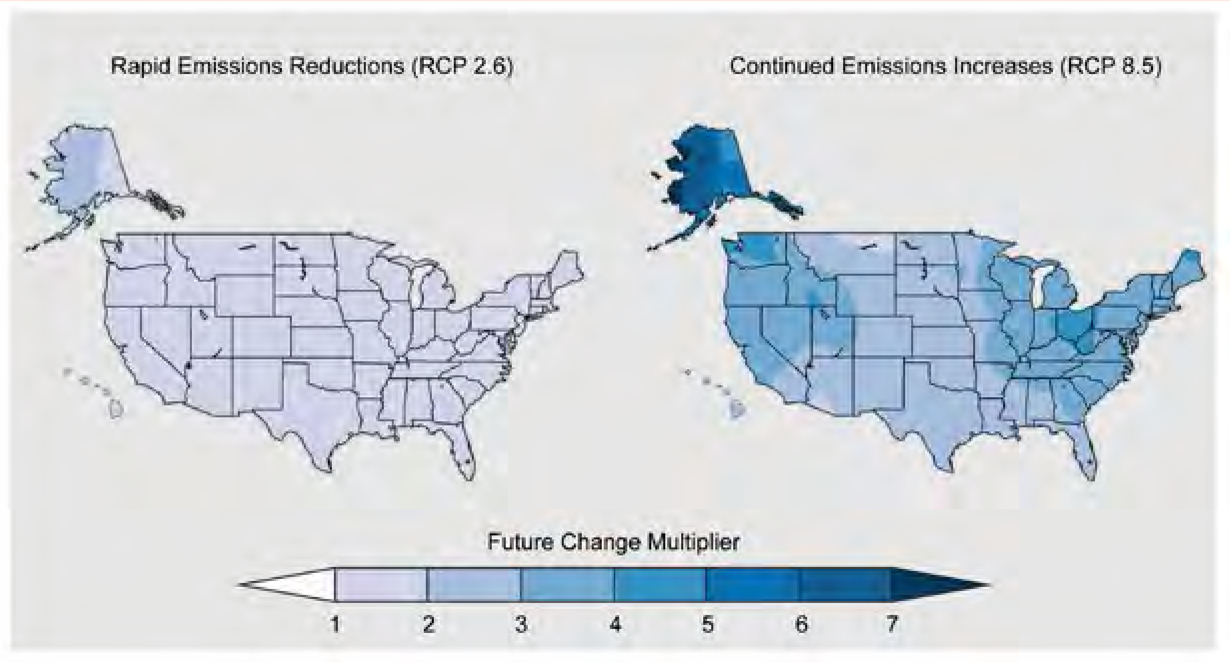

Figure 2.19. Maps show the increase in frequency of extreme daily precipitation events (a daily amount that now occurs once in 20 years) by the later part of this century (2081-2100) compared to the later part of last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the United States. Under the rapid emissions reduction scenario (RCP 2.6), these events would occur nearly twice as often. For the scenario assuming continued increases in emissions (RCP 8.5), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC).

Key Message 7: Extreme Weather

There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense, and cold waves less intense everywhere.

Heat waves are periods of abnormally hot weather lasting days to weeks.[48] Heat waves have generally become more frequent across the U.S. in recent decades, with western regions (including Alaska) setting records for numbers of these events in the 2000s. Tree ring data suggests that the drought over the last decade in the western U.S. represents the driest conditions in 800 years.[1,56] Most other regions in the country had their highest number of short-duration heat waves in the 1930s, when the multi-year severe drought of the Dust Bowl period, combined with deleterious land-use practices,[57] contributed to the intense summer heat through depletion of soil moisture and reduction of the moderating effects of evaporation.[58] However, the recent prolonged (multi-month) extreme heat has been unprecedented since the start of reliable instrumental records in 1895. The recent heat waves and droughts in Texas (2011) and the Midwest (2012) set records for highest monthly average temperatures, exceeding in some cases records set in the 1930s, including the highest monthly contiguous U.S. temperature on record (July 2012, breaking the July 1936 record) and the hottest summers on record in several states (New Mexico, Texas, Oklahoma, and Louisiana in 2011 and Colorado and Wyoming in 2012). For the spring and summer months, 2012 had the second largest area of record-setting monthly average temperatures, including a 26-state area from Wyoming to the East Coast. The summer (June-August) temperatures of 2012 ranked in the hottest 10% of the 118-year period of record in 28 states covering the Rocky Mountain states, the Great Plains, the Upper Midwest, and the Northeast. The new records included both hot daytime maximum temperatures and warm nighttime minimum temperatures.[59] Corresponding with this increase in extreme heat, the number of extreme cold waves has reached the lowest levels on record (since 1895).

Many more high temperature records are being broken as compared to low temperature records over the past three to four decades – another indicator of a warming climate.[60] The number of record low monthly temperatures has declined to the lowest levels since 1911, while the number of record high monthly temperatures has increased to the highest level since the 1930s. During this same period, there has been an increasing trend in persistently high nighttime temperature.[1] There are various reasons why low temperatures have increased more than high temperatures.[61]

In some areas, prolonged periods of record high temperatures associated with droughts contribute to dry conditions that are driving wildfires.[62] The meteorological situations that cause heat waves are a natural part of the climate system. Thus the timing and location of individual events may be largely a natural phenomenon, although even these may be affected by human-induced climate change.[63] However, there is emerging evidence that most of the increases of heat wave severity over the U.S. are likely due to human activity,[64] with a detectable human influence in recent heat waves in the southern Great Plains[1,65] as well as in Europe[7,62] and Russia.[60,66,67] The summer 2011 heat wave and drought in Texas was primarily driven by precipitation deficits, but the human contribution to climate change approximately doubled the probability that the heat was record-breaking.[68] So while an event such as this Texas heat wave and drought could be triggered by a naturally occurring event such as a deficit in precipitation, the chances for record-breaking temperature extremes has increased and will

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continue to increase as the global climate warms. Generally, the changes in climate are increasing the likelihood for these types of severe events.

The number of extremely hot days is projected to continue to increase over much of the United States, especially by late century. Summer temperatures are projected to continue rising, and a reduction of soil moisture, which exacerbates heat waves, is projected for much of the western and central U.S. in summer. Climate models project that the same summertime temperatures that ranked among the hottest 5% in 1950-1979 will occur at least 70% of the time by 2035-2064 in the U.S. if global emissions of heat-trapping gases continue to grow (as in the A2 scenario).[67] By the end of this century, what have previously been once-in-20-year extreme heat days (1-day events) are projected to occur every two or three years over most of the nation.[69,70] In other words, what now seems like an extremely hot day will become commonplace.

Projected Temperature Change of Hottest and Coldest Days

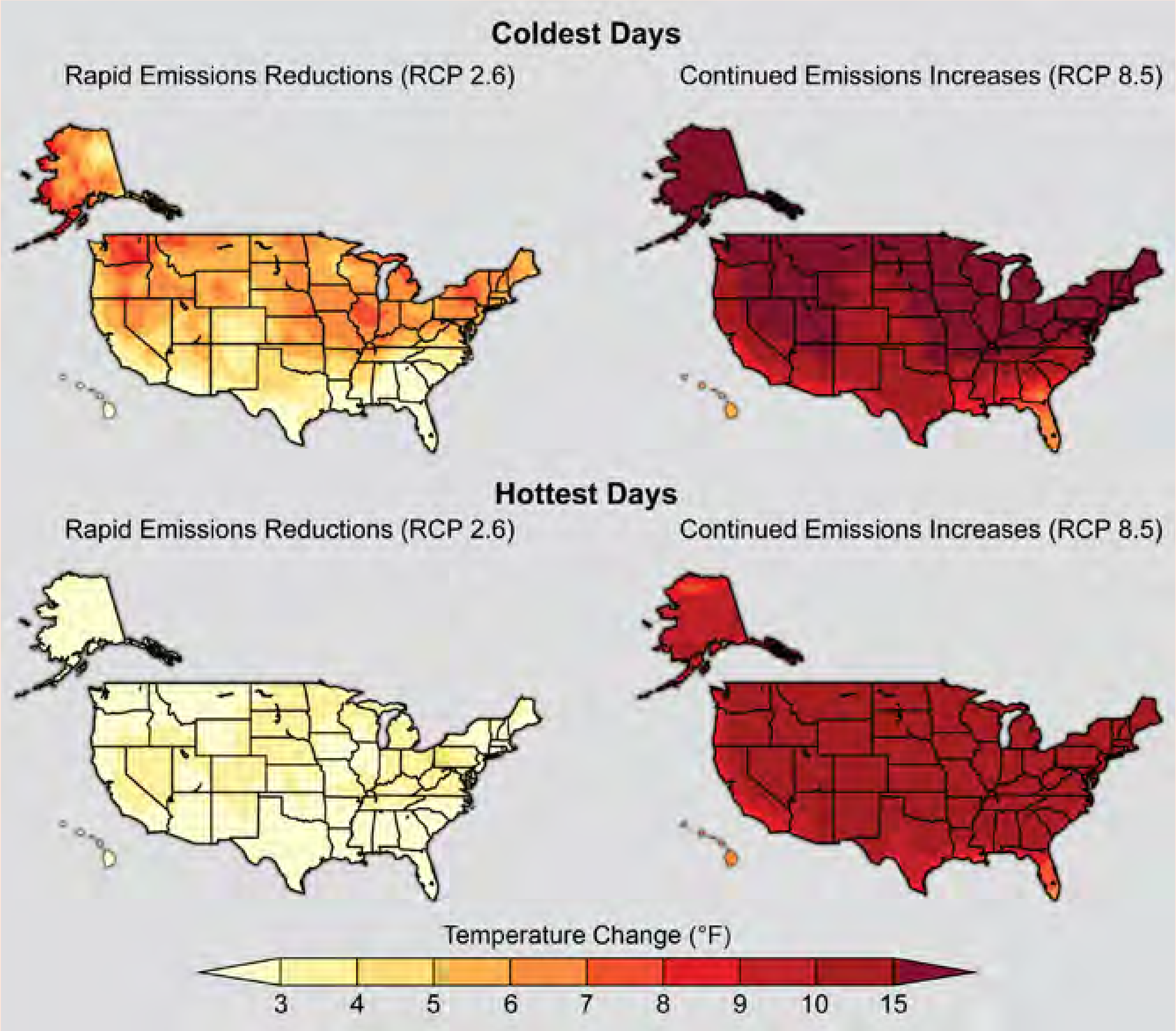

Figure 2.20. Change in surface air temperature at the end of this century (2081-2100) relative to the turn of the last century (1986-2005) on the coldest and hottest days under a scenario that assumes a rapid reduction in heat trapping gases (RCP 2.6) and a scenario that assumes continued increases in these gases (RCP 8.5). This figure shows estimated changes in the average temperature of the hottest and coldest days in each 20-year period. In other words, the hottest days will get even hotter, and the coldest days will be less cold. (Figure source: NOAA NCDC / CICS-NC).

There are significant trends in the magnitude of river flooding in many parts of the United States. When averaged over the entire nation, however, the increases and decreases cancel each other out and show no national level trend.[71] River flood magnitudes have decreased in the Southwest and increased in the eastern Great Plains, parts of the Midwest, and from the northern Appalachians into New England.[48] Figure 2.21 shows increasing trends in floods in green and decreasing trends in brown. The magnitude of these trends is illustrated by the size of the triangles.

Trends in Flood Magnitude

Figure 2.21. Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. Local areas can be affected by land-use change (such as dams). Most significant are the increasing trend for floods in the Midwest and Northeast and the decreasing trend in the Southwest. (Figure source: Peterson et al. 2013[48]).

These regional river flood trends are qualitatively consistent with trends in climate conditions associated with flooding. For example, average annual precipitation has increased in the Midwest and Northeast and decreased in the Southwest (Figure 2.12).[48] Recent soil moisture trends show general drying in the Southwest and moistening in the Northeast and northern Great Plains and Midwest (Ch 3: Water, Figure 3.2). These trends are in general agreement with the flood trends. Although there is a strong national upward trend in extreme precipitation and not in river flooding, the regional variations are similar. Extreme precipitation has been increasing strongly in the Great Plains, Midwest, and Northeast, where river flooding increases have been observed, and there is little trend in the Southwest, where river flooding has decreased. An exact correspondence is not necessarily expected since the seasonal timing of precipitation events makes a difference in whether river flooding occurs. The increase in extreme precipitation events has been concentrated in the summer and fall[52] when soil moisture is seasonally low and soils can absorb a greater fraction of rainfall. By contrast, many of the annual flood events occur in the spring when soil moisture is high. Thus, additional extreme rainfall events in summer and fall may not create sufficient runoff for the resulting streamflow to exceed spring flood magnitudes. However, these extreme precipitation events are often associated with local flash floods, a leading cause of death due to weather events (see “Flood Factors and Flood Types” in Ch. 3: Water).

Research into the effects of human-induced climate change on flood events is relatively new. There is evidence of a detectable human influence in recent flooding events in England and Wales[13] and in other specific events around the globe during 2011.[48] In general, heavier rains lead to a larger fraction of rainfall running off and, depending on the surface conditions, more potential for flooding.

Higher temperatures lead to increased rates of evaporation, including more loss of moisture through plant leaves. Even in areas where precipitation does not decrease, these increases in surface evaporation and loss of water from plants lead to more rapid drying of soils if the effects of higher temperatures are not offset by other changes (such as in wind speed or humidity).[72] As soil dries out, a larger proportion of the incoming heat from the sun goes into heating the soil and adjacent air rather than evaporating its moisture, resulting in hotter summers under drier climatic conditions.[73] Under higher emissions scenarios, widespread drought is projected to become more common over most of the central and southern United States.[56,74,75,76,77]

Projected Changes in Soil Moisture for the Western U.S.

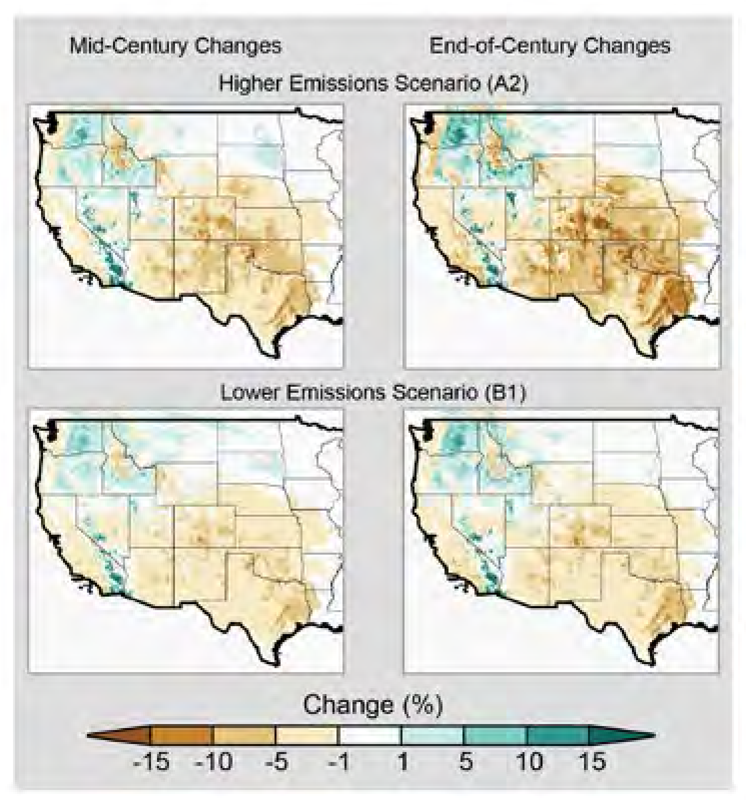

Figure 2.22. Average change in soil moisture compared to 1971-2000, as projected for the middle of this century (2041-2070) and late this century (2071-2100) under two emissions scenarios, a lower scenario (B1) and a higher scenario (A2).[75,77] The future drying of soils in most areas simulated by this sophisticated hydrologic model (Variable Infiltration Capacity or VIC model) is consistent with the future drought increases using the simpler Palmer Drought Severity Index (PDSI) metric. Only the western U.S. is displayed because model simulations were only run for this area. (Figure source: NOAA NCDC / CICS-NC).

Key Message 8: Changes in Hurricanes

The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.

There has been a substantial increase in most measures of Atlantic hurricane activity since the early 1980s, the period during which high-quality satellite data are available.[78,79] These include measures of intensity, frequency, and duration as well as the number of strongest (Category 4 and 5) storms. The ability to assess longer-term trends in hurricane activity is limited by the quality of available data. The historic record of Atlantic hurricanes dates back to the mid-1800s, and indicates other decades of high activity. However, there is considerable uncertainty in the record prior to the satellite era (early 1970s), and the further back in time one goes, the more uncertain the record becomes.[79]

The recent increases in activity are linked, in part, to higher sea surface temperatures in the region that Atlantic hurricanes form in and move through. Numerous factors have been shown to influence these local sea surface temperatures, including natural variability, human-induced emissions of heat-trapping gases, and particulate pollution. Quantifying the relative contributions of natural and human-caused factors is an active focus of research. Some studies suggest that natural variability, which includes the Atlantic Multidecadal Oscillation, is the dominant cause of the warming trend in the Atlantic since the 1970s,[80,81] while others argue that human-caused heat-trapping gases and particulate pollution are more important.[82]

Hurricane development, however, is influenced by more than just sea surface temperature. How hurricanes develop also depends on how the local atmosphere responds to changes in local sea surface temperatures, and this atmospheric response depends critically on the *cause* of the change.[83] For example, the atmosphere responds differently when local sea surface temperatures increase due to a local decrease of particulate pollution that allows more sunlight through to warm the ocean, versus when sea surface temperatures increase more uniformly around the world due to increased amounts of human-caused heat-trapping gases.[80,84] So the link between hurricanes and ocean temperatures is complex. Improving our

Observed Trends in Hurricane Power Dissipation

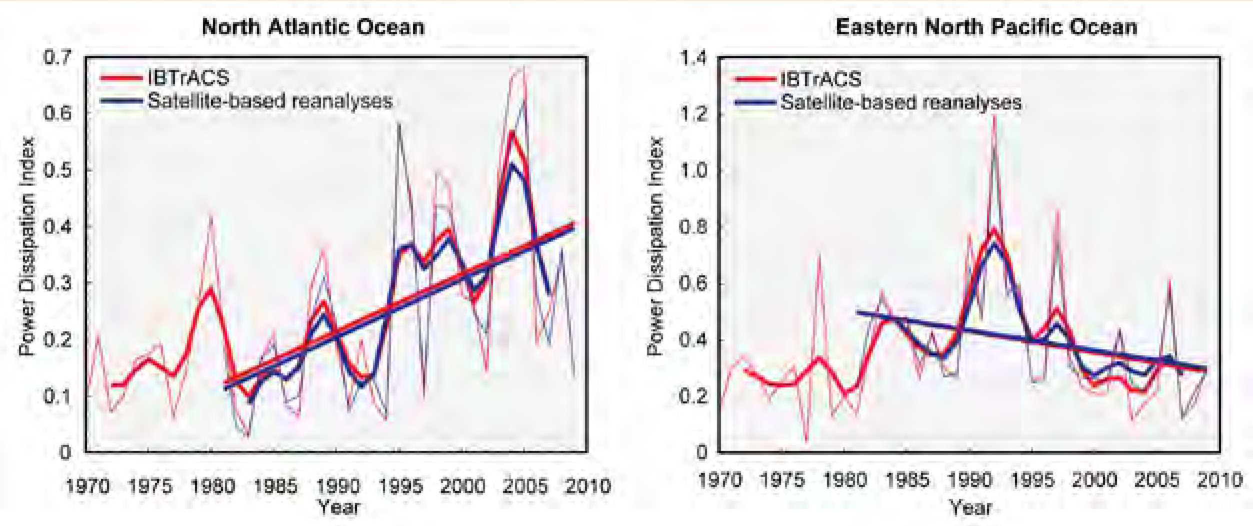

Figure 2.23. Recent variations of the Power Dissipation Index (PDI) in the North Atlantic and eastern North Pacific Oceans. PDI is an aggregate of storm intensity, frequency, and duration and provides a measure of total hurricane power over a hurricane season. There is a strong upward trend in Atlantic PDI, and a downward trend in the eastern North Pacific, both of which are well-supported by the reanalysis. Separate analyses (not shown) indicate a significant increase in the strength and in the number of the strongest hurricanes (Category 4 and 5) in the North Atlantic over this same time period. The PDI is calculated from historical data (IBTrACS[92]) and from reanalyses using satellite data (UW/NCDC & ADT-HURSAT[93,94]). IBTrACS is the International Best Track Archive for Climate Stewardship, UW/NCDC is the University of Wisconsin/NOAA National Climatic Data Center satellite-derived hurricane intensity dataset, and ADT-HURSAT is the Advanced Dvorak Technique–Hurricane Satellite dataset (Figure source: adapted from Kossin et al. 2007[93]).

understanding of the relationships between warming tropical oceans and tropical cyclones is another active area of research.

Changes in the average length and positions of Atlantic storm tracks are also associated with regional climate variability.[85] The locations and frequency of storms striking land have been argued to vary in opposing ways than basin-wide frequency. For example, fewer storms have been observed to strike land during warmer years even though overall activity is higher than average,[86] which may help to explain the lack of any clear trend in landfall frequency along the U.S. eastern and Gulf coasts.[87,88] Climate models also project changes in hurricane tracks and where they strike land.[89] The specific characteristics of the changes are being actively studied.

Other measures of Atlantic storm activity are projected to change as well.[87,90,91] By late this century, models, on average, project a slight decrease in the annual number of tropical cyclones, but an increase in the number of the strongest (Category 4 and 5) hurricanes. These projected changes are based on an average of projections from a number of individual models, and they represent the most likely outcome. There is some uncertainty in this as the individual models do not always agree on the amount of projected change, and some models may project an increase where others project a decrease. The models are in better agreement when projecting changes in hurricane precipitation – almost all existing studies project greater rainfall rates in hurricanes in a warmer climate, with projected increases of about 20% averaged near the center of hurricanes.


NOAA Environmental Visualization Lab

North Atlantic hurricanes have increased in intensity, frequency, and duration since the early 1980s.

Key Message 9: Changes in Storms

Winter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, are uncertain and are being studied intensively.

Trends in the occurrences of storms, ranging from severe thunderstorms to winter storms to hurricanes, are subject to much greater uncertainties than trends in temperature and variables that are directly related to temperature (such as snow and ice cover, ocean heat content, and sea level). Recognizing that the impacts of changes in the frequency and intensity of these storms can easily exceed the impacts of changes in average temperature or precipitation, climate scientists are actively researching the connections between climate change and severe storms. There has been a sizeable upward trend in the number of storms causing large financial and other losses.[95] However, there are societal contributions to this trend, such as increases in population and wealth.[52]

Severe Convective Storms

Tornadoes and other severe thunderstorm phenomena frequently cause as much annual property damage in the U.S. as do hurricanes, and often cause more deaths. Recent research has yielded insights into the connections between global warming and the factors that cause tornadoes and severe thunderstorms (such as atmospheric instability and increases in wind speed with altitude[96]). Although these relationships are still being explored, a recent study suggests a projected increase in the frequency of conditions favorable for severe thunderstorms.[97]

Winter Storms

For the entire Northern Hemisphere, there is evidence of an increase in both storm frequency and intensity during the cold season since 1950,[98] with storm tracks having shifted slightly towards the poles.[99,100] Extremely heavy snowstorms increased in number during the last century in northern and eastern parts of the United States, but have been less frequent since 2000.[52,101] Total seasonal snowfall has generally decreased in southern and some western areas,[102] increased in the northern Great Plains and Great Lakes region,[102,103] and not changed in other areas, such as the Sierra Nevada, although snow is melting earlier in the year and more precipitation is falling as rain versus snow.[104] Very snowy winters have generally been decreasing in frequency in most regions over the last 10 to 20 years, although the Northeast has been seeing a normal number of such winters.[105] Heavier-than-normal snowfalls recently observed in the Midwest and Northeast U.S. in some years, with little snow in other years, are consistent with indications of increased blocking (a large scale pressure pattern with little or no movement) of the wintertime circulation of the Northern Hemisphere.[106] However, conclusions about trends in blocking have been found to depend on the method of analysis,[107] so the assessment and attribution of trends in blocking remains an active research area. Overall snow cover has decreased in the Northern Hemisphere, due in part to higher temperatures that shorten the time snow spends on the ground.[108]

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Variation of Storm Frequency and Intensity during the Cold Season (November – March)

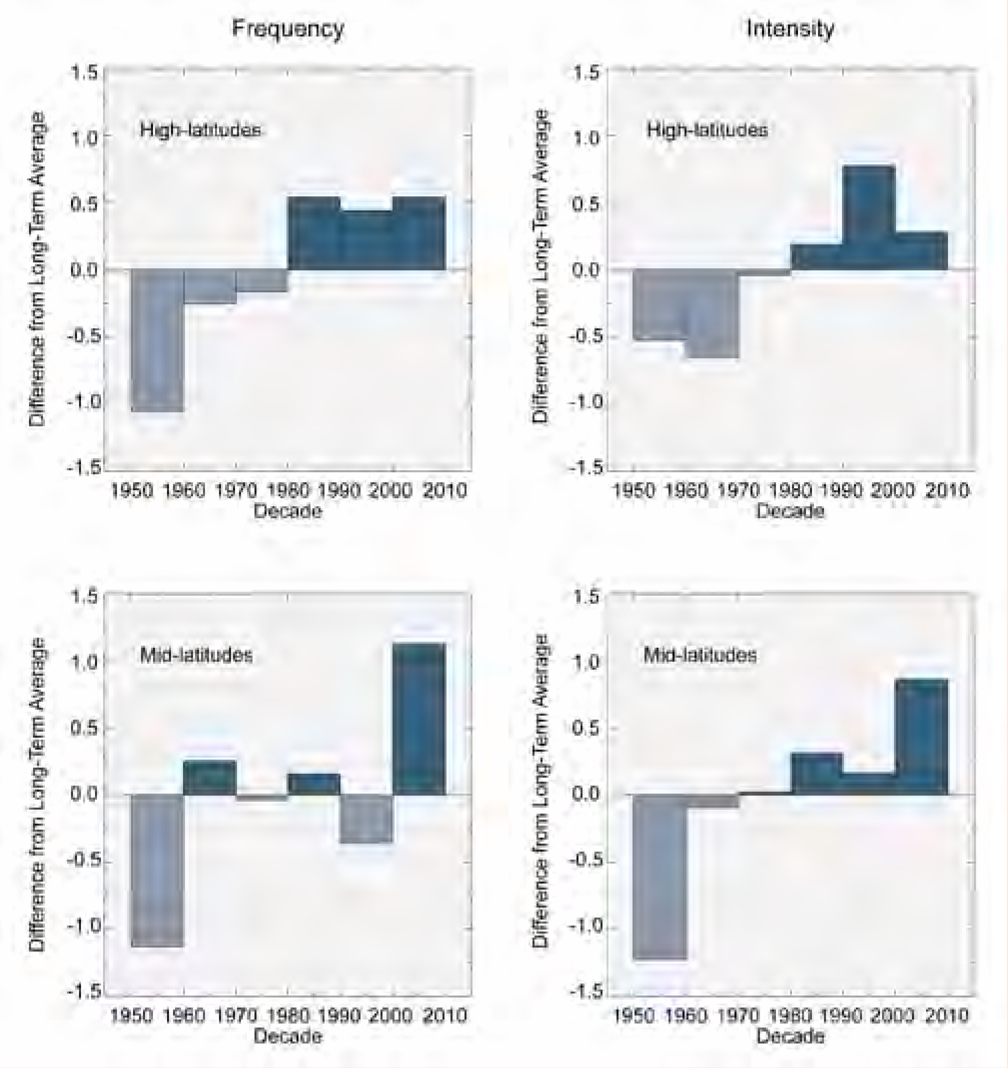

Figure 2.24. Variation of winter storm frequency and intensity during the cold season (November-March) for high latitudes (60-90°N) and mid-latitudes (30-60°N) of the Northern Hemisphere over the period 1949-2010. The bar for each decade represents the difference from the long-term average. Storm frequencies have increased in middle and high latitudes, and storm intensities have increased in middle latitudes. (Figure source: updated from CCSP 2008[109]).

Key Message 10: Sea Level Rise

Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

The oceans are absorbing over 90% of the increased atmospheric heat associated with emissions from human activity.[110] Like mercury in a thermometer, water expands as it warms up (this is referred to as "thermal expansion") causing sea levels to rise. Melting of glaciers and ice sheets is also contributing to sea level rise at increasing rates.[111]

Since the late 1800s, tide gauges throughout the world have shown that global sea level has risen by about 8 inches. A new data set (Figure 2.25) shows that this recent rise is much greater than at any time in at least the past 2000 years.[112] Since 1992, the rate of global sea level rise measured by satellites has been roughly twice the rate observed over the last century, providing evidence of additional acceleration.[113]

Projecting future rates of sea level rise is challenging. Even the most sophisticated climate models, which explicitly represent Earth's physical processes, cannot simulate rapid changes in ice sheet dynamics, and thus are likely to underestimate future sea level rise. In recent years, "semi-empirical" methods have been developed to project future rates of sea level rise based on a simple statistical relationship between past rates of globally averaged temperature change and sea level rise. These models suggest a range of additional sea level rise from about 2 feet to as much as 6 feet by 2100, depending on emissions scenario.[114,115,116,117] It is not clear, however, whether these statistical relationships will hold in the future, or that they fully explain historical behavior.[118] Regardless of the amount of change by 2100, however, sea level rise is expected to continue well beyond this century as a result of both past and future emissions from human activities.

North Atlantic Sea Level Change

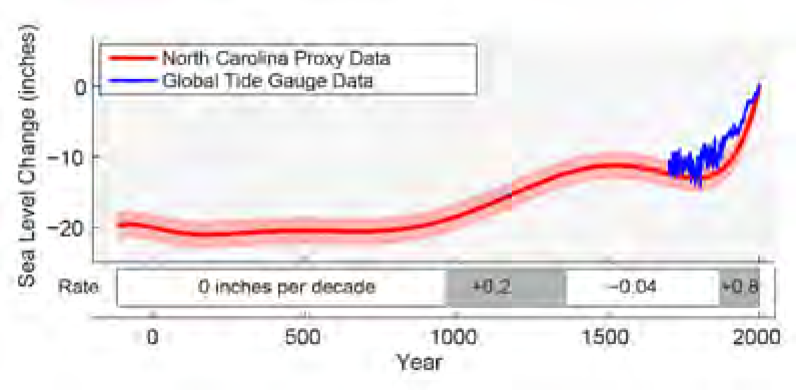

Figure 2.25. Sea level change in the North Atlantic Ocean relative to the year 2000 based on data collected from North Carolina[112] (red line, pink band shows the uncertainty range) compared with a reconstruction of global sea level rise based on tide gauge data from 1750 to present[127] (blue line). (Figure source: NASA Jet Propulsion Laboratory).

Scientists are working to narrow the range of sea level rise projections for this century. Recent projections show that for even the lowest emissions scenarios, thermal expansion of ocean waters[119] and the melting of small mountain glaciers[120] will result in 11 inches of sea level rise by 2100, even without any contribution from the ice sheets in Greenland and Antarctica. This suggests that about 1 foot of global sea level rise by 2100 is probably a realistic low end. On the high end, recent work suggests that 4 feet is plausible.[22,115,121] In the context of risk-based analysis, some decision makers may wish to use a wider range of scenarios, from 8 inches to 6.6 feet by 2100.[122,123] In particular, the high end of these scenarios may be useful for decision makers with a low tolerance for risk (see Figure 2.26 on global sea level rise).[122,123] Although scientists cannot yet assign likelihood to any particular scenario, in general, higher emissions scenarios that lead to more warming would be expected to lead to higher amounts of sea level rise.

Nearly 5 million people in the U.S. live within 4 feet of the local high-tide level (also known as mean higher high water). In the next several decades, storm surges and high tides could combine with sea level rise and land subsidence to further increase flooding in many of these regions.[124] Sea level rise will not stop in 2100 because the oceans take a very long time to respond to warmer conditions at the Earth's surface. Ocean waters will therefore continue to warm and sea level will continue to rise for many centuries at rates equal to or higher than that of the current century.[125] In fact, recent research has suggested that even present day carbon dioxide levels are sufficient to cause Greenland to melt completely over the next several thousand years.[126]

Past and Projected Changes in Global Sea Level Rise

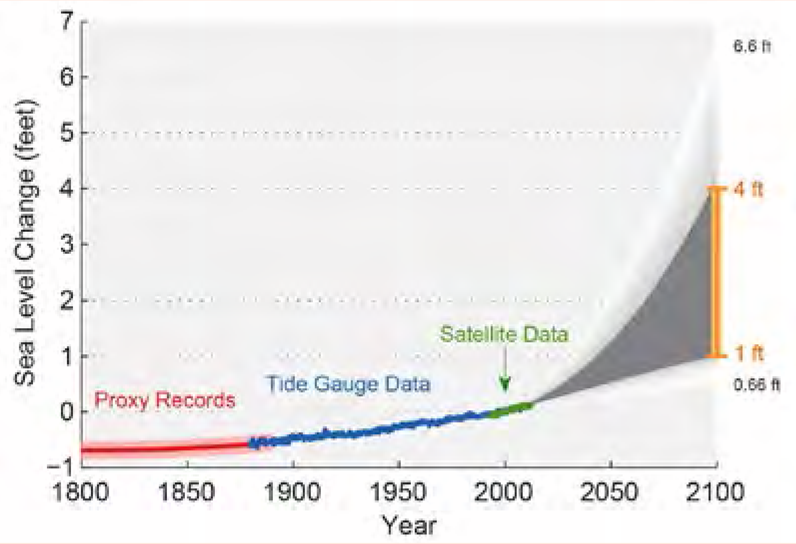

Figure 2.26. Estimated, observed, and possible future amounts of global sea level rise from 1800 to 2100, relative to the year 2000. Estimates from proxy data[112] (for example, based on sediment records) are shown in red (1800-1890, pink band shows uncertainty), tide gauge data are shown in blue for 1880-2009,[113] and satellite observations are shown in green from 1993 to 2012. [128] The future scenarios range from 0.66 feet to 6.6 feet in 2100.[123] These scenarios are not based on climate model simulations, but rather reflect the range of possible scenarios based on other scientific studies. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100, which falls within the larger risk-based scenario range. The large projected range reflects uncertainty about how glaciers and ice sheets will react to the warming ocean, the warming atmosphere, and changing winds and currents. As seen in the observations, there are year-to-year variations in the trend. (Figure source: NASA Jet Propulsion Laboratory).

Key Message 11: Melting Ice

Rising temperatures are reducing ice volume and surface extent on land, lakes, and sea. This loss of ice is expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century.

Rising temperatures across the U.S. have reduced lake ice, sea ice, glaciers, and seasonal snow cover over the last few decades.[111] In the Great Lakes, for example, total winter ice coverage has decreased by 63% since the early 1970s.[172] This includes the entire period since satellite data became available. When the record is extended back to 1963 using pre-satellite data,[129] the overall trend is less negative because the Great Lakes region experienced several extremely cold winters in the 1970s.

Sea ice in the Arctic has also decreased dramatically since the late 1970s, particularly in summer and autumn. Since the satellite record began in 1978, minimum Arctic sea ice extent (which occurs in early to mid-September) has decreased by more than 40%.[131] This decline is unprecedented in the historical record, and the reduction of ice volume and thickness is even greater. Ice thickness decreased by more than 50% from 1958-1976 to 2003-2008,[132] and the percentage of the March ice cover made up of thicker ice (ice that has survived a summer melt season) decreased from 75% in the mid-1980s to 45% in 2011.[133] Recent analyses indicate a decrease of 36% in autumn sea ice volume over the past decade.[134] The 2012 sea ice minimum broke the preceding record (set in 2007) by more than 200,000 square miles. Ice loss increases Arctic warming by replacing white, reflective ice with dark water that absorbs more energy from the sun. More open water can also increase snowfall over northern land areas[135] and increase the north-south meanders of the jet stream, consistent with the occurrence of unusually cold and snowy winters at mid-latitudes in several recent years.[106,135] Significant uncertainties remain at this time in interpreting the effect of Arctic ice changes on mid-latitudes.[107]

The loss of sea ice has been greater in summer than in winter. The Bering Sea, for example, has sea ice only in the winter-spring portion of the year, and shows no trend in surface area covered by ice over the past 30 years. However, seasonal ice in the Bering Sea and elsewhere in the Arctic is thin and susceptible to rapid melt during the following summer.

The seasonal pattern of observed loss of Arctic sea ice is generally consistent with simulations by global climate models, in which the extent of sea ice decreases more rapidly in summer than in winter. However, the models tend to underestimate the amount of decrease since 2007. Projections by these models indicate that the Arctic Ocean is expected to become essentially ice-free in summer before mid-century under scenarios that assume continued growth in global emissions, although sea ice would still form in winter.[136,137] Models that best match historical trends project a nearly sea ice-free Arctic in summer by the 2030s,[138] and extrapolation of the present observed trend suggests an even earlier ice-free Arctic in summer.[139] However, even during a long-term decrease, occasional temporary increases in Arctic summer sea ice can be expected over timescales of a decade or so because of natural variability.[140] The projected reduction of winter sea ice is only about 10% by 2030,[141] indicating that the Arctic will shift to a more seasonal sea ice pattern. While this ice will be thinner, it will cover much of the same area now covered by sea ice in winter.

While the Arctic is an ocean surrounded by continents, Antarctica is a continent surrounded by ocean. Nearly all of the sea ice in the Antarctic melts each summer, and changes there are more complicated than in the Arctic. While Arctic sea ice has

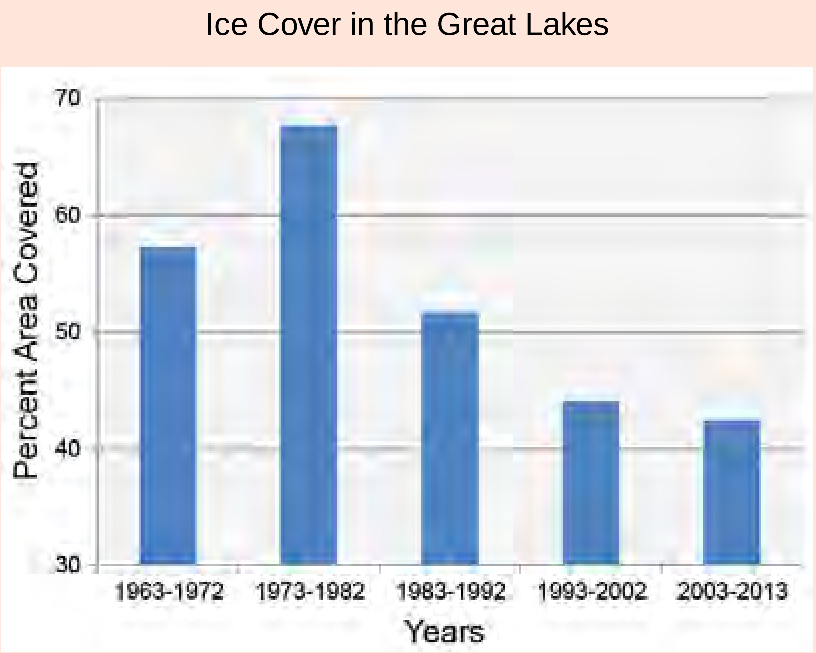

Figure 2.27. Bars show decade averages of annual maximum Great Lakes ice coverage from the winter of 1962-1963, when reliable coverage of the entire Great Lakes began, to the winter of 2012-2013. Bar labels indicate the end year of the winter; for example, 1963-1972 indicates the winter of 1962-1963 through the winter of 1971-1972. Only the most recent period includes the eleven years from 2003 to 2013. (Data updated from Bai and Wang, 2012[130]).

Decline in Arctic Sea Ice Extent

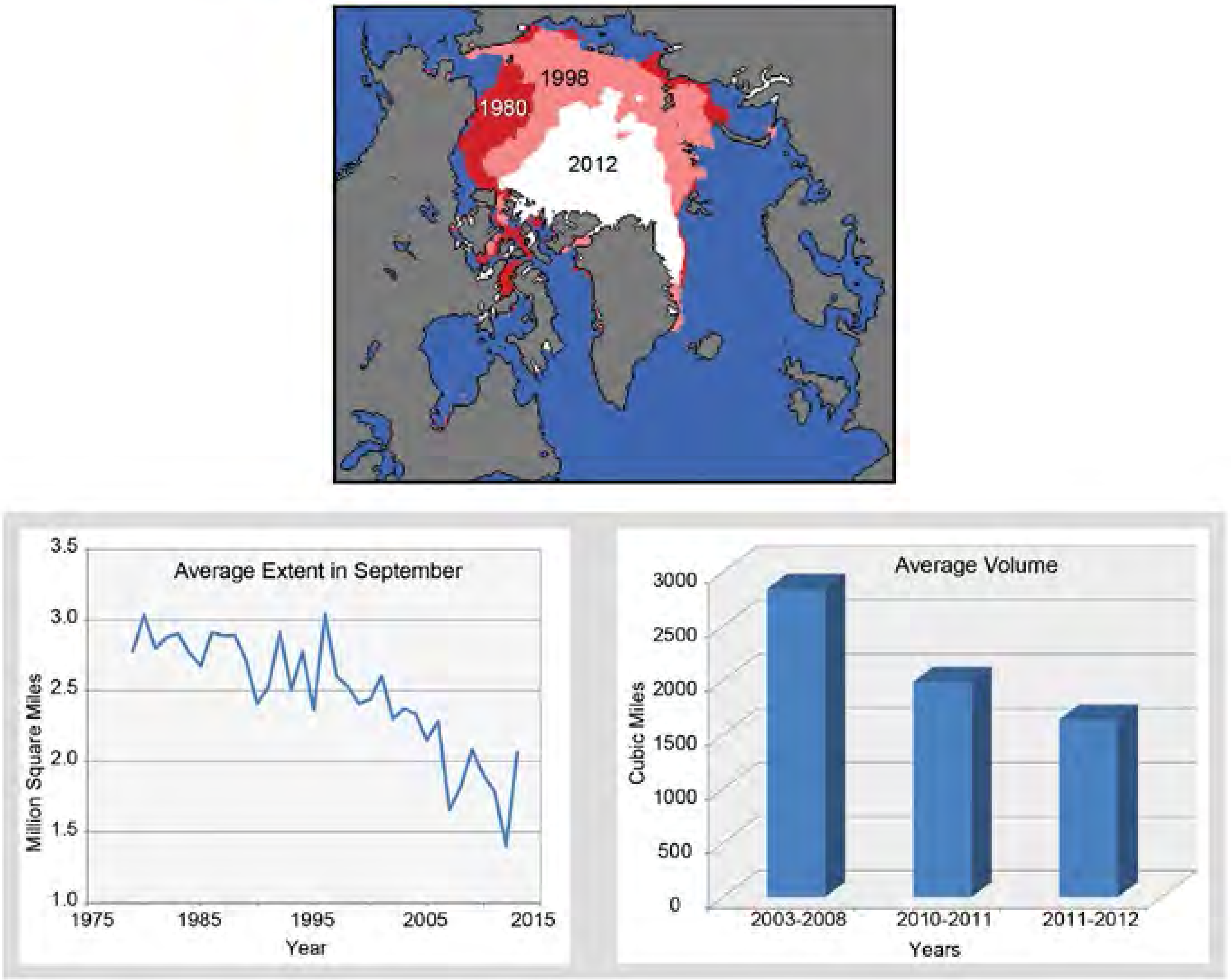

Figure 2.28. Summer Arctic sea ice has declined dramatically since satellites began measuring it in 1979. The extent of sea ice in September 2012, shown in white in the top figure, was more than 40% below the median for 1979-2000. The graph on the bottom left shows annual variations in September Arctic sea ice extent for 1979-2013. It is also notable that the ice has become much thinner in recent years, so its total volume (bottom right) has declined even more rapidly than the extent.[111] (Figure and data from National Snow and Ice Data Center).

been strongly decreasing, there has been a slight increase in sea ice in Antarctica.[142] Explanations for this include changes in winds that directly affect ice drift as well as the properties of the surrounding ocean,[143] and that winds around Antarctica may have been affected by stratospheric ozone depletion.[144]

Snow cover on land has decreased over the past several decades,[145] especially in late spring.[146] Each of five recent years (2008-2012) has set a new record for minimum snow extent in June in Eurasia, as did three of those five years in North America.

The surface of the Greenland Ice Sheet has been experiencing summer melting over increasingly large areas during the past several decades. In the decade of the 2000s, the daily melt area summed over the warm season was double the corresponding amounts of the 1970s,[147] culminating in summer surface melt that was far greater (97% of the Greenland Ice Sheet area) in 2012 than in any year since the satellite record began in 1979. More importantly, the rate of mass loss from the Greenland Ice Sheet's marine-terminating outlet glaciers has accelerated in recent decades, leading to predictions that the proportion of global sea level rise coming from Greenland will continue to increase.[148] Glaciers terminating on ice shelves and on land are also losing mass, but the rate of loss has not accelerated over the past decade.[149] As discussed in Key Message 10, the dynamics of the Greenland Ice Sheet are generally not included in present global climate models and sea level rise projections.

Projected Arctic Sea Ice Decline

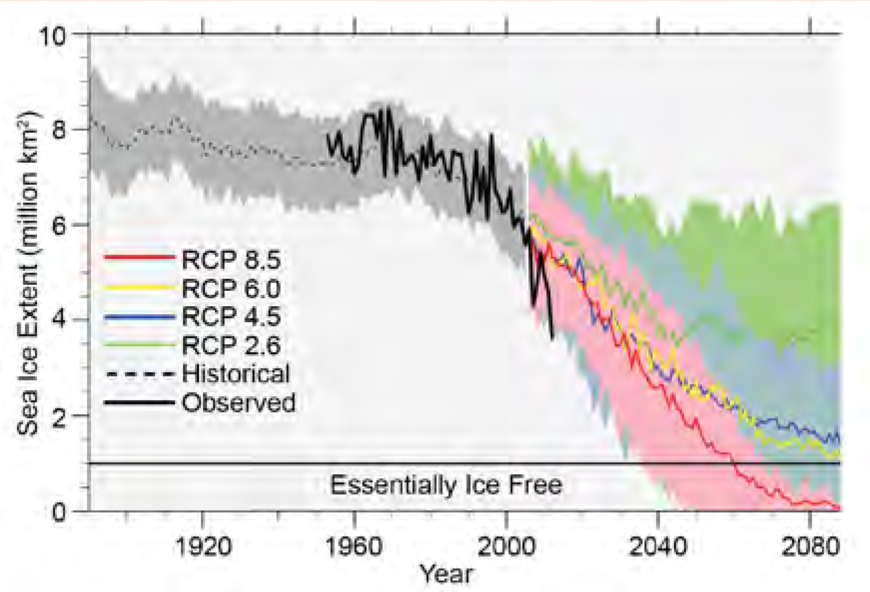

Figure 2.29. Model simulations of Arctic sea ice extent for September (1900-2100) based on observed concentrations of heat-trapping gases and particles (through 2005) and four scenarios. Colored lines for RCP scenarios are model averages (CMIP5) and lighter shades of the line colors denote ranges among models for each scenario. Dotted gray line and gray shading denotes average and range of the historical simulations through 2005. The thick black line shows observed data for 1953-2012. These newer model (CMIP5) simulations project more rapid sea ice loss compared to the previous generation of models (CMIP3) under similar forcing scenarios, although the simulated September ice losses under all scenarios still lag the observed loss of the past decade. Extrapolation of the present observed trend suggests an essentially ice-free Arctic in summer before mid-century.[139] The Arctic is considered essentially ice-free when the areal extent of ice is less than one million square kilometers. (Figure source: adapted from Stroeve et al. 2012[136]).

Glaciers are retreating and/or thinning in Alaska and in the lower 48 states. In addition, permafrost temperatures are increasing over Alaska and much of the Arctic. Regions of discontinuous permafrost in interior Alaska (where annual average soil temperatures are already close to 32°F) are highly vulnerable to thaw. Thawing permafrost releases carbon dioxide and methane – heat-trapping gases that contribute to even more warming. Recent estimates suggest that the potential release of carbon from permafrost soils could add as much as 0.4ºF to 0.6ºF of warming by 2100.[150] Methane emissions have been detected from Alaskan lakes underlain by permafrost,[151] and measurements suggest potentially even greater releases from thawing methane hydrates in the Arctic continental shelf of the East Siberian Sea.[152] However, the response times of Arctic methane hydrates to climate change are quite long relative to methane's lifetime in the atmosphere (about a decade).[153] More generally, the importance of Arctic methane sources relative to other methane sources, such as wetlands in warmer climates, is largely unknown. The potential for a self-reinforcing feedback between permafrost thawing and additional warming contributes additional uncertainty to the high end of the range of future warming. The projections of future climate shown throughout this report do not include the additional increase in temperature associated with this thawing.

Key Message 12: Ocean Acidification

The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems.

As human-induced emissions of carbon dioxide (CO_2) build up in the atmosphere, excess CO_2 is dissolving into the oceans where it reacts with seawater to form carbonic acid, lowering ocean pH levels ("acidification") and threatening a number of marine ecosystems.[154] Currently, the oceans absorbs about a quarter of the CO_2 humans produce every year.[155] Over the last 250 years, the oceans have absorbed 560 billion tons of CO_2, increasing the acidity of surface waters by 30%.[156,157,158] Although the average oceanic pH can vary on interglacial timescales,[156] the current observed rate of change is roughly 50 times faster than known historical change.[159,160] Regional factors such as coastal upwelling,[161] changes in discharge rates from rivers and glaciers,[162] sea ice loss,[163] and urbanization[164] have created "ocean acidification hotspots" where changes are occurring at even faster rates.

The acidification of the oceans has already caused a suppression of carbonate ion concentrations that are critical for marine calcifying animals such as corals, zooplankton, and shellfish. Many of these animals form the foundation of the marine food web. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Ocean acidification puts this important resource at risk.

Observations have shown that the northeastern Pacific Ocean, including the Arctic and sub-Arctic seas, is particularly susceptible to significant shifts in pH and calcium carbonate saturation levels. Recent analyses show that large areas of the oceans along the U.S. west coast,[157,165] the Bering Sea, and the western Arctic Ocean[158,166] will become difficult for calcifying animals within the next 50 years. In particular, animals that form calcium carbonate shells, including corals, crabs, clams, oysters, and tiny free-swimming snails called pteropods, could be particularly vulnerable, especially during the larval stage.[167,168,169]

As Oceans Absorb CO_2, They Become More Acidic

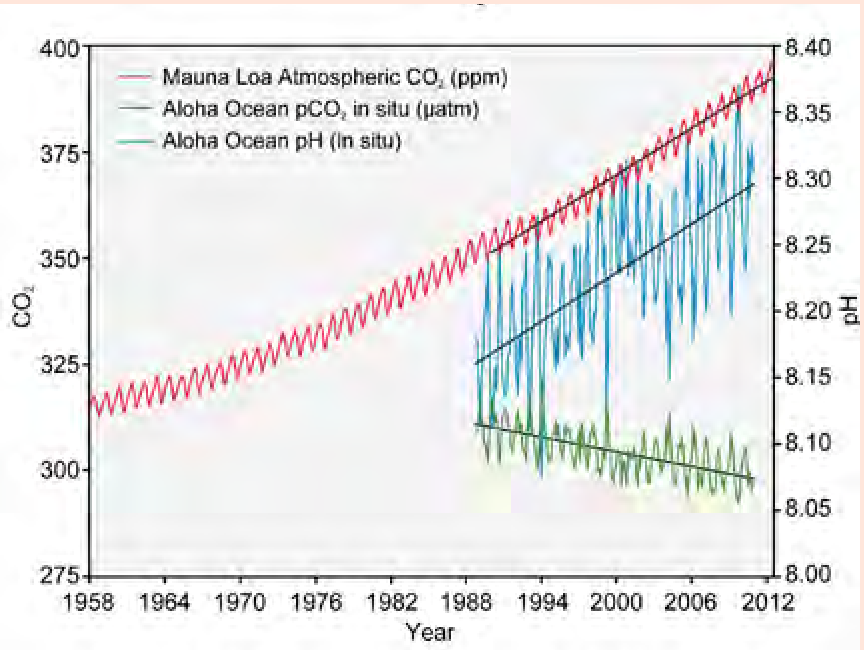

Figure 2.30. The correlation between rising levels of CO_2 in the atmosphere (red) at Mauna Loa and rising CO_2 levels (blue) and falling pH (green) in the nearby ocean at Station Aloha. As CO_2 accumulates in the ocean, the water becomes more acidic (the pH declines). (Figure source: modified from Feely et al. 2009[157]).

Projections indicate that in higher emissions pathways, such as SRES A2 or RCP 8.5, current pH could be reduced from the current level of 8.1 to as low as 7.8 by the end of the century.[158] Such large changes in ocean pH have probably not been experienced on the planet for the past 100 million years, and it is unclear whether and how quickly ocean life could adapt to such rapid acidification.[159]

Shells Dissolve in Acidified Ocean Water

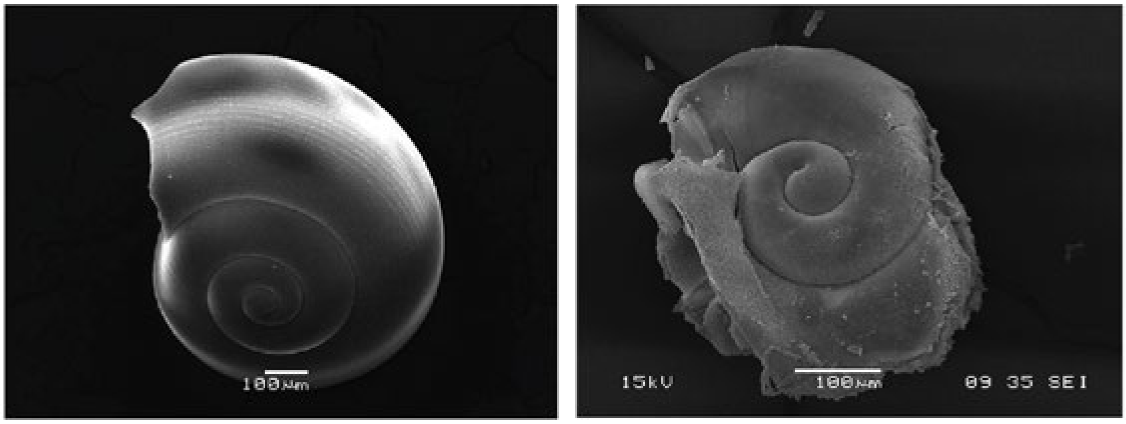

Figure 2.31. Pteropods, or "sea butterflies," are free-swimming sea snails about the size of a small pea. Pteropods are eaten by marine species ranging in size from tiny krill to whales and are an important source of food for North Pacific juvenile salmon. The photos above show what happens to a pteropod's shell in seawater that is too acidic. The left panel shows a shell collected from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod collected in a region where the water is more acidic (Photo credits: (left) Bednaršek et al. 2012;[168] (right) Nina Bednaršek).

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

Development of the key messages involved discussions of the lead authors and accompanying analyses conducted via one in-person meeting plus multiple teleconferences and email exchanges from February thru September 2012. The authors reviewed 80 technical inputs provided by the public, as well as other published literature, and applied their professional judgment.

Key message development also involved the findings from four special workshops that related to the latest scientific understanding of climate extremes. Each workshop had a different theme related to climate extremes, had approximately 30 attendees (the CMIP5 meeting had more than 100), and the workshops resulted in a paper.[55] The first workshop was held in July 2011, titled Monitoring Changes in Extreme Storm Statistics: State of Knowledge.[52] The second was held in November 2011, titled Forum on Trends and Causes of Observed Changes in Heatwaves, Coldwaves, Floods, and Drought.[48] The third was held in January 2012, titled Forum on Trends in Extreme Winds, Waves, and Extratropical Storms along the Coasts.[98] The fourth, the CMIP5 results workshop, was held in March 2012 in Hawai'i, and resulted in an analysis of CMIP5 results relative to climate extremes in the United States.[55]

The Chapter Author Team's discussions were supported by targeted consultation with additional experts. Professional expertise and judgment led to determining "key vulnerabilities." A consensus-based approach was used for final key message selection.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Global climate is changing and this change is apparent across a wide range of observations. The global warming of the past 50 years is primarily due to human activities.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence for changes in global climate arises from multiple analyses of data from in-situ, satellite, and other records undertaken by many groups over several decades.[3] Changes in the mean state have been accompanied by changes in the frequency and nature of extreme events.[4] A substantial body of analysis comparing the observed changes to a broad range of climate simulations consistently points to the necessity of invoking human-caused changes to adequately explain the observed climate system behavior.[5,7] The influence of human impacts on the climate system has also been observed in a number of individual climate variables.[6,12,13,14,15,16,17] A discussion of the slowdown in temperature increase with associated references (for example, Balmaseda et al. 2013; Easterling and Wehner 2009[19,27]) is included in the chapter.

The Climate Science Supplement Appendix provides further discussion of types of emissions or heat-trapping gases and particles, and future projections of human-related emissions. Supplemental Message 4 of the Appendix provides further details on attribution of observed climate changes to human influence.

New information and remaining uncertainties

Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and particularly regional, scales, and especially for extreme events and our ability to simulate and attribute such changes using climate models. Innovative new approaches to climate data analysis, continued improvements in climate modeling, and instigation and maintenance of reference quality observation networks such as the U.S. Climate Reference Network (http://www.ncdc.noaa.gov/crn/) all have the potential to reduce uncertainties.

Assessment of confidence based on evidence

There is **very high** confidence that global climate is changing and this change is apparent across a wide range of observations, given the evidence base and remaining uncertainties. All observational evidence is consistent with a warming climate since the late 1800s.

There is **very high** confidence that the global climate change of the past 50 years is primarily due to human activities, given the evidence base and remaining uncertainties. Recent changes have been consistently attributed in large part to human factors across a very broad range of climate system characteristics.

Key message #2 Traceable Account

Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.

Description of evidence base
The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence of continued global warming is based on past observations of climate change and our knowledge of the climate system's response to heat-trapping gases. Models have projected increased temperature under a number of different scenarios.[8,32,33]

That the planet has warmed is "unequivocal,"[8] and is corroborated though multiple lines of evidence, as is the conclusion that the causes are very likely human in origin (see also Appendices 3 and 4). The evidence for future warming is based on fundamental understanding of the behavior of heat-trapping gases in the atmosphere. Model simulations provide bounds on the estimates of this warming.

New information and remaining uncertainties
The trends described in the 2009 report[1] have continued, and our understanding of the data and ability to model the many facets of the climate system have increased substantially.

There are several major sources of uncertainty in making projections of climate change. The relative importance of these changes over time.

In the next few decades, the effects of natural variability will be an important source of uncertainty for climate change projections.

Uncertainty in future human emissions becomes the largest source of uncertainty by the end of this century.

Uncertainty in how sensitive the climate is to increased concentrations of heat-trapping gases is especially important beyond the next few decades. Recent evidence lends further confidence about climate sensitivity (see Appendix 3: Climate Science Supplement).

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Uncertainty in natural climate drivers, for example how much solar output will change over this century, also affects the accuracy of projections.

Assessment of confidence based on evidence
Given the evidence base and remaining uncertainties, confidence is **very high** that the global climate is projected to continue to change over this century and beyond**.**

The statement on the magnitude of the effect also has **very high** confidence.

Key message #3 Traceable Account

U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the nation's warmest on record. Temperatures in the United States are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

Description of evidence base
The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics

were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence for the long-term increase in temperature is based on analysis of daily maximum and minimum temperature observations from the U.S. Cooperative Observer Network (http://www.nws.noaa.gov/om/coop/). With the increasing understanding of U.S. temperature measurements, a temperature increase has been observed, and temperature is projected to continue rising.[36,37,38] Observations show that the last decade was the warmest in over a century. A number of climate model simulations were performed to assess past, and to forecast future, changes in climate; temperatures are generally projected to increase across the United States.

The section entitled "Quantifying U.S. Temperature Rise" explains the rational for using the range 1.3°F to 1.9°F in the key message.

All peer-reviewed studies to date satisfying the assessment process agree that the U.S. has warmed over the past century and in the past several decades. Climate model simulations consistently project future warming and bracket the range of plausible increases.

New information and remaining uncertainties

Since the 2009 National Climate Assessment,[1] there have been substantial advances in our understanding of the U.S. temperature record (Appendix 3: Climate Science, Supplemental Message 7).[36,37,38]

A potential uncertainty is the sensitivity of temperature trends to adjustments that account for historical changes in station location, temperature instrumentation, observing practice, and siting conditions. However, quality analyses of these uncertainties have not found any major issues of concern affecting the conclusions made in the key message (Appendix 3: Climate Science, Supplemental Message 7). (for example, Williams et al. 2012[38]).

While numerous studies (for example, Fall et al. 2011; Vose et al. 2012; Williams et al. 2012[37,38]) verify the efficacy of the adjustments, the information base can be improved in the future through continued refinements to the adjustment approach. Model biases are subject to changes in physical effects on climate; for example, model biases can be affected by snow cover and hence are subject to change as a warming climate changes snow cover.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** in the key message. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

KEY MESSAGE #4 TRACEABLE ACCOUNT

The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Nearly all studies to date published in the peer-reviewed literature (for example, Dragoni et al. 2011; EPA 2012; Jeong et al. 2011[40,41,43]) agree that the frost-free and growing seasons have lengthened. This is most apparent in the western United States. Peer-reviewed studies also indicate that continued lengthening will occur if concentrations of heat-trapping gases continue to rise. The magnitude of future changes based on model simulations is large in the context of historical variations.

Evidence that the length of the frost-free season is lengthening is based on extensive analysis of daily minimum temperature observations from the U.S. Cooperative Observer Network. The geographic variations in increasing number of frost-free days are similar to the regional variations in mean temperature. Separate analysis of surface data also indicates a trend towards an earlier onset of spring.[40,41,43,45]

New information and remaining uncertainties

A key issue (uncertainty) is the potential effect on observed trends of climate monitoring station inhomogeneities (differences), particularly those arising from instrumentation changes. A second key issue is the extent to which observed regional variations (more lengthening in the west/less in the east) will persist into the future.

Local temperature biases in climate models contribute to the uncertainty in projections.

Viable avenues to improving the information base are to investigate the sensitivity of observed trends to potential biases introduced by station inhomogeneities and to investigate the causes of observed regional variations.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that the length of the frost-free season (also referred to as the growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western U.S, affecting ecosystems, gardening, and agriculture. Given the evidence base, confidence is **very high** that across the U.S., the growing season is projected to continue to lengthen.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence of long-term change in precipitation is based on analysis (for example, Kunkel et al. 2013[170]) of daily observations from the U.S. Cooperative Observer Network. Published work shows the regional differences in precipitation.[47,48] Evidence of future change is based on our knowledge of the climate system's response to heat-trapping gases and an understanding of the regional mechanisms behind the projected changes (for example, IPCC 2007[8]).

New information and remaining uncertainties

A key issue (uncertainty) is the sensitivity of observed precipitation trends to historical changes in station location, rain gauges, and observing practice. A second key issue is the ability of climate models to simulate precipitation. This is one of the more challenging aspects of modeling of the climate system, because precipitation involves not only large-scale processes that are well-resolved by models but small-scale process, such as convection, that must be parameterized in the current generation of global and regional climate models. However, our understanding of the physical basis for these changes has solidified and the newest set of climate model simulations (CMIP5) continues to show high-latitude increases and subtropical decreases in precipitation. For most of the contiguous U.S., studies[171] indicate that the models currently do not detect a robust anthropogenic influence to observed changes, suggesting that observed changes are principally of natural origins. Thus, confident projections of precipitation changes are limited to the northern and southern areas of the contiguous U.S. that are part of the global pattern of observed and robust projected changes that can be related to anthropogenic forcing. Furthermore, for the first time in the U.S. National Climate Assessment, a confidence statement is made that some projected precipitation changes are deemed small. It is incorrect to attempt to validate or invalidate climate model simulations of observed trends in these regions and/or seasons, as such simulations are not designed to forecast the precise timing of natural variations.

Shifts in precipitation patterns due to changes in other sources of air pollution, such as sulfate aerosols, are uncertain and are an active research topic.

Viable avenues to improving the information base are to investigate the sensitivity of observed trends to potential biases introduced by station changes, and to investigate the causes of observed regional variations.

A number of peer-reviewed studies (for example, McRoberts and Nielsen-Gammon 2011; Peterson et al. 2013[47,48]) document precipitation increases at the national scale as well as regional-scale increases and decreases. The variation in magnitude and pattern of future changes from climate model simulations is large relative to observed (and modeled) historical variations.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high** that average U.S. precipitation has increased since 1900, with some areas having had increases greater than the national average, and some areas having had decreases.

Confidence is **high,** given the evidence base and uncertainties, that more winter and spring precipitation is projected for the northern U.S., and less for the Southwest, over this century in the higher emissions scenarios. Confidence is **medium** that human-induced precipitation changes will be small compared to natural variations in all seasons over large portions of the U.S. in the lower emissions scenarios. Confidence is **medium** that human-induced precipitation changes will be small compared to natural variations in the summer and fall over large portions of the U.S. in the higher emissions scenarios.

KEY MESSAGE #6 TRACEABLE ACCOUNT

Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence that extreme precipitation is increasing is based primarily on analysis[52,55,170] of hourly and daily precipitation observations from the U.S. Cooperative Observer Network, and is supported by observed increases in atmospheric water vapor.[75] Recent publications have projected an increase in extreme precipitation events,[52,137] with some areas getting larger increases[1] and some getting decreases.[54,55]

Nearly all studies to date published in the peer-reviewed literature agree that extreme precipitation event number and intensity have risen, when averaged over the United States. The pattern of change for the wettest day of the year is projected to roughly follow that of the average precipitation, with both increases and decreases across the U.S. Extreme hydrologic events are projected to increase over most of the U.S.

New information and remaining uncertainties

A key issue (uncertainty) is the ability of climate models to simulate precipitation. This is one of the more challenging aspects of modeling of the climate system because precipitation involves not only large-scale processes that are well-resolved by models but also small-scale process, such as convection, that must be parameterized in the current generation of global and regional climate models.

Viable avenues to improving the information base are to perform some long, very high-resolution simulations of this century's climate under different emissions scenarios.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **high** that heavy downpours are increasing in most regions of the U.S., with especially large increases in the Midwest and Northeast.

Confidence is **high** that further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas, given the evidence base and uncertainties.

KEY MESSAGE #7 TRACEABLE ACCOUNT

There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense, and cold waves less intense everywhere.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Analysis of U.S. temperature records indicates that record cold events are becoming progressively less frequent relative to record high events.[60,170] There is evidence for the corresponding trends in a global framework.[7,66] A number of publications have explored the increasing trend of heat waves.[7,62,69] Additionally, heat waves observed in the southern Great Plains,[1] Europe,[7,62] and Russia[60,66,67] have now been shown to have a higher probability of having occurred because of human-induced climate change.

Some parts of the U.S. have been seeing changing trends for floods and droughts over the last 50 years, with some evidence for human influence.[13,48,62] In the areas of increased flooding in parts of the Great Plains, Midwest, and Northeast, increases in both total precipitation and extreme precipitation have been observed and may be contributing to the flooding increases. However, when averaging over the entire contiguous U.S., there is no overall trend in flood magnitudes.[71] A number of publications project drought as becoming a more normal condition over much of the southern and central U.S. (most recent references: Dai 2012; Hoerling et al. 2012; Wehner et al. 2011[75,76]).

Analyses of U.S. daily temperature records indicate that low records are being broken at a much smaller rate than high records, and at the smallest rate in the historical record.[60,170] However, in certain localized regions, natural variations can be as large or larger than the human induced change.

New information and remaining uncertainties

The key uncertainty regarding projections of future drought is how soil moisture responds to precipitation changes and potential evaporation increases. Most studies indicate that many parts of the U.S. will experience drier soil conditions but the amount of that drying is uncertain.

Natural variability is also an uncertainty affecting projections of extreme event occurrences in shorter timescales (several years to decades), but the changes due to human influence become larger relative to natural variability as the timescale lengthens. Stakeholders should view the occurrence of extreme events in the context of increasing probabilities due to climate change.

Continuation of long term temperature and precipitation observations is critical to monitoring trends in extreme weather events.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **high** for the entire key message.

Heat waves have become more frequent and intense, and confidence is **high** that heat waves everywhere are projected to become more intense in the future.

Confidence is **high** that cold waves have become less frequent and intense across the nation.

Confidence is **high** that there have been regional trends in floods and droughts.

Confidence is **high** that droughts in the Southwest are projected to become more intense.

Key message #8 Traceable Account

The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Recent studies suggest that the most intense Atlantic hurricanes have become stronger since the early 1980s.[93] While this is still the subject of active research, this trend is projected to continue.[90,91]

New information and remaining uncertainties

Detecting trends in Atlantic and eastern North Pacific hurricane activity is challenged by a lack of consistent historical data and limited understanding of all of the complex interactions between the atmosphere and ocean that influence hurricanes.[87,88]

While the best analyses to date[87,91] suggest an increase in intensity and in the number of the most intense hurricanes over this century, there remain significant uncertainties.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

High confidence that the intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have increased substantially since the early 1980s.

Low confidence in relative contributions of human and natural causes in the increases.

Medium confidence that hurricane intensity and rainfall rates are projected to increase as the climate continues to warm.

Key message #9 Traceable Account

Winter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, are uncertain and are being studied intensively.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Current work[98] has provided evidence of the increase in frequency and intensity of winter storms, with the storm tracks shifting poleward,[99,100] but some areas have experienced a decrease in winter storm frequency.[1] Although there are some indications of increased blocking (a large-scale pressure pattern with little or no movement) of the wintertime circulation of the Northern Hemisphere,[106] the assessment and attribution of trends in blocking remain an active research area.[107] Some recent research has provided insight into the connection of global warming to tornadoes and severe thunderstorms.[96]

New information and remaining uncertainties

Winter storms and other types of severe storms have greater uncertainties in their recent trends and projections, compared to hurricanes (Key Message 8). The text for this key message explicitly acknowledges the state of knowledge, pointing out “what we don’t know.” There has been a sizeable upward trend in the number of storm events causing large financial and other losses.[95]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

Confidence is **medium** that winter storms have increased slightly in frequency and intensity, and that their tracks have shifted northward over the U.S.

Confidence is **low** on other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds.

KEY MESSAGE #10 TRACEABLE ACCOUNT

Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Nearly all studies to date published in the peer-reviewed literature agree that global sea level has risen during the past century, and that it will continue to rise over the next century.

Tide gauges throughout the world have documented rising sea levels during the last 130 years. This rise has been further confirmed over the past 20 years by satellite observations, which are highly accurate and have nearly global coverage. Recent studies have shown current sea level rise rates are increasing[112,123] and project that future sea level rise over the rest of this century will be faster than that of the last 100 years (Appendix 3: Climate Science, Supplemental Message 12).[123]

New information and remaining uncertainties

The key issue in predicting future rates of global sea level rise is to understand and predict how ice sheets in Greenland and Antarctica will react to a warming climate. Current projections of global sea level rise do not account for the complicated behavior of these giant ice slabs as they interact with the atmosphere, the ocean and the land. Lack of knowledge about the ice sheets and their behavior is the primary reason that projections of global sea level rise includes such a wide range of plausible future conditions.

Early efforts at semi-empirical models suggested much higher rates of sea level rise (as much as 6 feet by 2100).[115,117] More recent work suggests that a high end of 3 to 4 feet is more plausible.[115,116,121] It is not clear, however, whether these statistical relationships will hold in the future or that they are appropriate in modeling past behavior, thus calling their reliability into question.[118] Some decision-makers may wish to consider a broader range of scenarios such as 8 inches or 6.6 feet by 2100 in the context of risk-based analysis.[122,123]

Assessment of confidence based on evidence

Given the evidence and uncertainties, confidence is **very high** that global sea level has risen during the past century, and that it will continue to rise over this century, with **medium** confidence that global sea level rise will be in the range of 1 to 4 feet by 2100.

KEY MESSAGE #11 TRACEABLE ACCOUNT

Rising temperatures are reducing ice volume and surface extent on land, lakes, and sea. This loss of ice is expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

There have been a number of publications reporting decreases in ice on land[147] and glacier recession. Evidence that winter lake ice and summer sea ice are rapidly declining is based on satellite data and is incontrovertible.[111,172]

Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining,[131] with even greater reductions in ice thickness[132,133] and volume,[134] and that if heat-trapping gas concentrations continue to rise, an essentially ice-free Arctic ocean will be realized sometime during this century (for example, Stroeve et al. 2012[136]). September 2012 had the lowest levels of Arctic ice in recorded history. Great Lakes ice should follow a similar trajectory. Glaciers will generally retreat, except for a small percentage of glaciers that experience dynamical surging.[111] Snow cover on land has decreased over the past several decades.[145] The rate of permafrost degradation is complicated by changes in snow cover and vegetation.

New information and remaining uncertainties

The rate of sea ice loss through this century is a key issue (uncertainty), which stems from a combination of large differences in projections between different climate models, natural climate variability and uncertainty about future rates of fossil fuel emissions. This uncertainty is illustrated in Figure 2.29, showing the CMIP5-based projections (adapted from Stroeve et al. 2012[136]).

Viable avenues to improving the information base are determining the primary causes of the range of different climate model projections and determining which climate models exhibit the best ability to reproduce the observed rate of sea-ice loss.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **very high** that rising temperatures are reducing ice volume and extent on land, lakes, and sea, and that this loss of ice is expected to continue.

Confidence is **very high** that the Arctic Ocean is projected to become virtually ice-free in summer by mid-century.

KEY MESSAGE #12 TRACEABLE ACCOUNT

The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

The oceans currently absorb a quarter of the CO_2 the caused by human activities.[155] Publications have shown that this absorption causes the ocean to become more acidic (for example, Doney et al. 2009[154]). Recent publications demonstrate the adverse effects further acidification will have on marine life.[158,165,169]

New information and remaining uncertainties

Absorption of CO_2 of human origin, reduced pH, and lower calcium carbonate ($CaCO_3$) saturation in surface waters, where the bulk of oceanic production occurs, are well verified from models, hydrographic surveys, and time series data.[158] The key issue (uncertainty) is how future levels of ocean acidity will affect marine ecosystems.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **very high** that oceans are absorbing about a quarter of emitted CO_2.

Very high for trend of ocean acidification; **low-to-medium** for intensifying impacts on marine ecosystems. Our present understanding of projected ocean acidification impacts on marine organisms stems largely from short-term laboratory and mesocosm experiments, although there are also examples based on actual ocean observations; consequently, the response of individual

SECTORS

Cherry farmers in Michigan, insurance agents in Florida, and water managers in Arizona are among the millions of Americans already living with – and adapting to – a range of climate change impacts. Higher temperatures, rising sea levels, and more extreme precipitation events are altering the work of first responders, city planners, engineers, and others, influencing economic sectors from coast to coast. Agriculture, energy, transportation, and more, are all affected by climate change in concrete ways. American communities are contending with these changes now, and will be doing so increasingly in the future.

Sectors of our economy do not exist in isolation. Forest management activities, for example, affect and are affected by water supply, changing ecosystems, impacts to biological diversity, and energy availability. Water supply and energy use are completely intertwined, since water is used to generate energy, and energy is required to pump, treat, and deliver water – which means that irrigation-dependent farmers and urban dwellers are linked as well. Human health is affected by water supply, agricultural practices, transportation systems, energy availability, and land use, among other factors – touching the lives of patients, nurses, county health administrators, and many others. Human social systems and communities are directly affected by extreme weather events and changes in natural resources such as water availability and quality; they are also affected both directly and indirectly by ecosystem health.

This report addresses some of these topics individually, focusing on the climate-related risks and opportunities that occur within individual sectors, while others take a cross-sector approach. Single-sector chapters focus on:

- Water resources
- Energy production and use
- Transportation
- Agriculture
- Forests
- Human health
- Ecosystems and biodiversity

Six crosscutting chapters address how climate change interacts with multiple sectors. These cover the following topics:

- Energy, water, and land use
- Urban infrastructure and vulnerability
- Indigenous peoples, lands, and resources
- Land use and land cover
- Rural communities
- Biogeochemical cycles

A common theme is that these sectors are interconnected in many ways. These intricate connections mean that changes in one sector are often amplified or reduced through links to other sectors. Another theme is how decisions can influence a cascade of events that affect individual and national vulnerability and/or resiliency to climate change across multiple sectors. This "systems approach" helps to reveal, for example, how adaptation and mitigation strategies are part of dynamic and interrelated systems. In this way, for example, adaptation plans for future coastal infrastructure are connected with the kinds of mitigation strategies that are – or are not – put into place today, since the amount of future sea level rise will differ according to various societal decisions about current and future emissions. These chapters also address the importance of underlying vulnerabilities and the ways they may influence risks associated with climate change.

The chapters in the following section assess risks in the selected sectors, and include both observations of existing impacts associated with climate change, as well as projected impacts over the next several decades and beyond.

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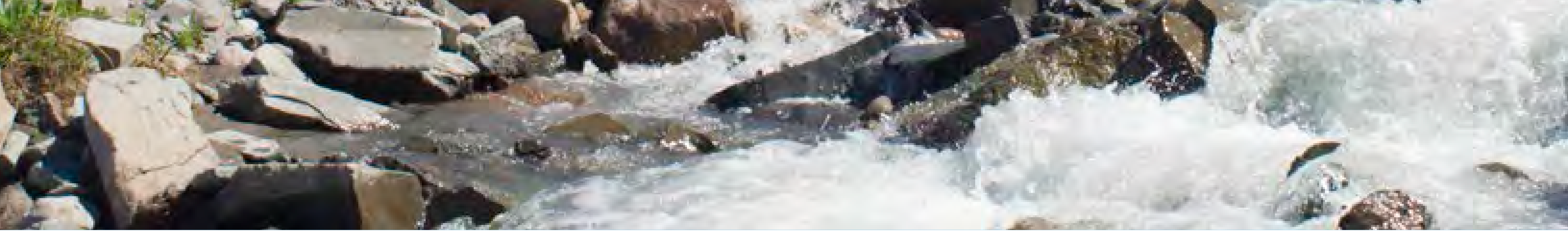

Climate Change Impacts in the United States

CHAPTER 3
WATER RESOURCES

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3 WATER RESOURCES

KEY MESSAGES


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Climate Change Impacts on the Water Cycle

1. **Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.**
2. **Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.**
3. **Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.**
4. **Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.**
5. **Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.**
6. **Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.**

Climate Change Impacts on Water Resources Use and Managment

7. **Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.**
8. **Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.**
9. **Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the United States.**

Adaptation and Institutional Responses

10. **In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.**
11. **Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.**

This chapter contains three main sections: climate change impacts on the water cycle, climate change impacts on water resources use and management, and adaptation and institutional responses. Key messages for each section are summarized above.

The cycle of life is intricately joined with the cycle of water.

— Jacques-Yves Cousteau

Climate Change Impacts on the Water Cycle

Water cycles constantly from the atmosphere to the land and the oceans (through precipitation and runoff) and back to the atmosphere (through evaporation and the release of water from plant leaves), setting the stage for all life to exist. The water cycle is dynamic and naturally variable, and societies and ecosystems are accustomed to functioning within this variability. However, climate change is altering the water cycle in multiple ways over different time scales and geographic areas, presenting unfamiliar risks and opportunities.

Key Message 1: Changing Rain, Snow, and Runoff

Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Annual average precipitation over the continental U.S. as a whole increased by close to two inches (0.16 inches per decade) between 1895 and 2011.[1,2] In recent decades, annual average precipitation increases have been observed across the Midwest, Great Plains, the Northeast, and Alaska, while decreases have been observed in Hawai'i and parts of the Southeast and Southwest (Ch. 2: Our Changing Climate, Figure 2.12). Average annual precipitation is projected to increase across the northern U.S., and decrease in the southern U.S., especially the Southwest. (Ch. 2: Our Changing Climate, Figures 2.14 and 2.15).[3]

The number and intensity of very heavy precipitation events (defined as the heaviest 1% of all daily events from 1901 to 2012) have been increasing significantly across most of the United States. The amount of precipitation falling in the heaviest daily events has also increased in most areas of the United States (Ch. 2: Our Changing Climate, Figure 2.17). For example, from 1950 to 2007, daily precipitation totals with 2-, 5-, and 10-year average recurrence periods increased in the Northeast and western Great Lakes.[4] Very heavy precipitation events are projected to increase everywhere (Ch. 2: Our Changing Climate, Figure 2.19).[5] Heavy precipitation events that historically occurred once in 20 years are projected to occur as frequently as every 5 to 15 years by late this century.[6] The number and magnitude of the heaviest precipitation events is projected to increase everywhere in the United States (Ch. 2: Our Changing Climate, Figure 2.13).

Dry spells are also projected to increase in length in most regions, especially in the southern and northwestern portions of the contiguous United States (Ch. 2: Our Changing Climate, Figure 2.13). Projected changes in total average annual precipitation are generally small in many areas, but both wet and dry extremes (heavy precipitation events

Projected Changes in Snow, Runoff, and Soil Moisture

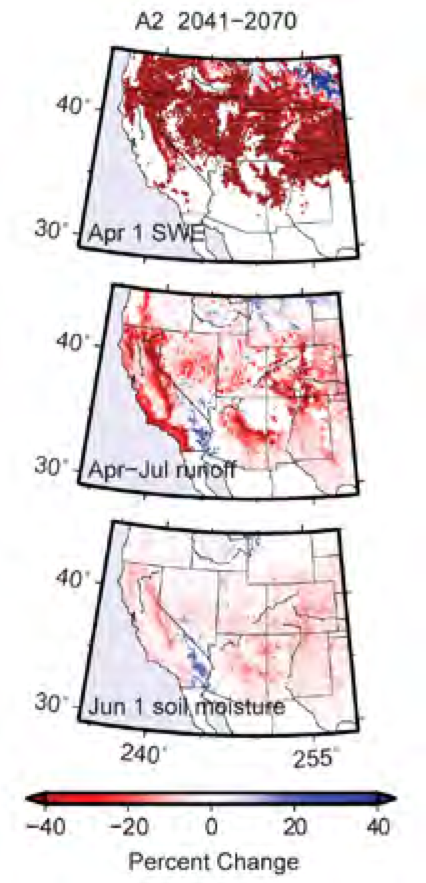


Figure 3.1. These projections, assuming continued increases in heat-trapping gas emissions (A2 scenario; Ch. 2: Our Changing Climate), illustrate: a) major losses in the water content of the snowpack that fills western rivers (snow water equivalent, or SWE); b) significant reductions in runoff in California, Arizona, and the central Rocky Mountains; and c) reductions in soil moisture across the Southwest. The changes shown are for mid-century (2041-2070) as percentage changes from 1971-2000 conditions (Figure source: Cayan et al. 2013[18]).

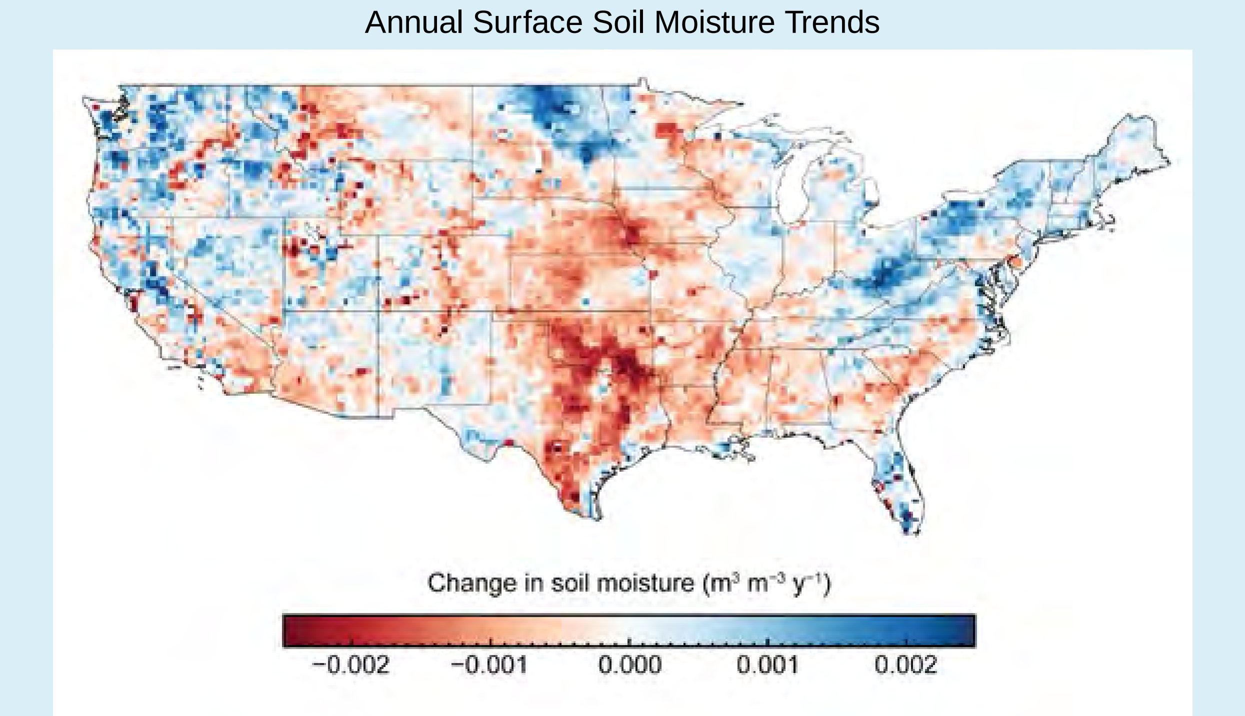


Figure 3.2. Changes in annual surface soil moisture per year over the period 1988 to 2010 based on multi-satellite datasets. Surface soil moisture exhibits wetting trends in the Northeast, Florida, upper Midwest, and Northwest, and drying trends almost everywhere else. (Images provided by W. Dorigo[35]).

and length of dry spells) are projected to increase substantially almost everywhere.

The timing of peak river levels has changed in response to warming trends. Snowpack and snowmelt-fed rivers in much of the western U.S. have earlier peak flow trends since the middle of the last century, including the past decade (Ch. 2: Our Changing Climate).[7,8] This is related to declines in spring snowpack, earlier snowmelt-fed streamflow, and larger percentages of precipitation falling as rain instead of snow. These changes have taken place in the midst of considerable year-to-year variability and long-term natural fluctuations of the western U.S. climate, as well as other influences, such as the effects of dust and soot on snowpacks.[7,9] There are both natural and human influences on the observed trends.[10,11] However, in studies specifically designed to differentiate between natural and human-induced causes, up to 60% of these changes have been attributed to human-induced climate warming,[10] but only among variables that are more responsive to warming than to precipitation variability, such as the effect of air temperature on snowpack.[12]

Other historical changes related to peak river-flow have been observed in the northern Great Plains, Midwest, and Northeast,[13,14] along with striking reductions in lake ice cover (Ch. 2: Our Changing Climate).[15,16]

Permafrost is thawing in many parts of Alaska, a trend that not only affects habitats and infrastructure but also mobilizes subsurface water and reroutes surface water in ways not previously witnessed.[17] Nationally, all of these trends are projected to become even more pronounced as the climate continues to warm (Figure 3.1).

Evapotranspiration (ET – the evaporation of moisture from soil, on plants and trees, and from water bodies; and transpiration, the use and release of water from plants), is the second largest component of the water cycle after precipitation. ET responds to temperature, solar energy, winds, atmospheric humidity, and moisture availability at the land surface and regulates amounts of soil moisture, groundwater recharge, and runoff.[19] Transpiration comprises between 80% and 90% of total ET on land (Ch. 6: Agriculture).[20] In snowy settings, sublimation of snow and ice (loss of snow and ice directly into water vapor without passing through a liquid stage) can increase these returns of water to the atmosphere, sometimes in significant amounts.[21] These interactions complicate estimation and projection of regional losses of water from the land surface to the atmosphere.

Globally-averaged ET increased between 1982 and 1997 but stopped increasing, or has decreased, since about 1998.[22] In North America, the observed ET decreases occurred in water-rich rather than water-limited areas. Factors contributing to these ET decreases are thought to include decreasing wind

Seasonal Surface Soil Moisture Trends

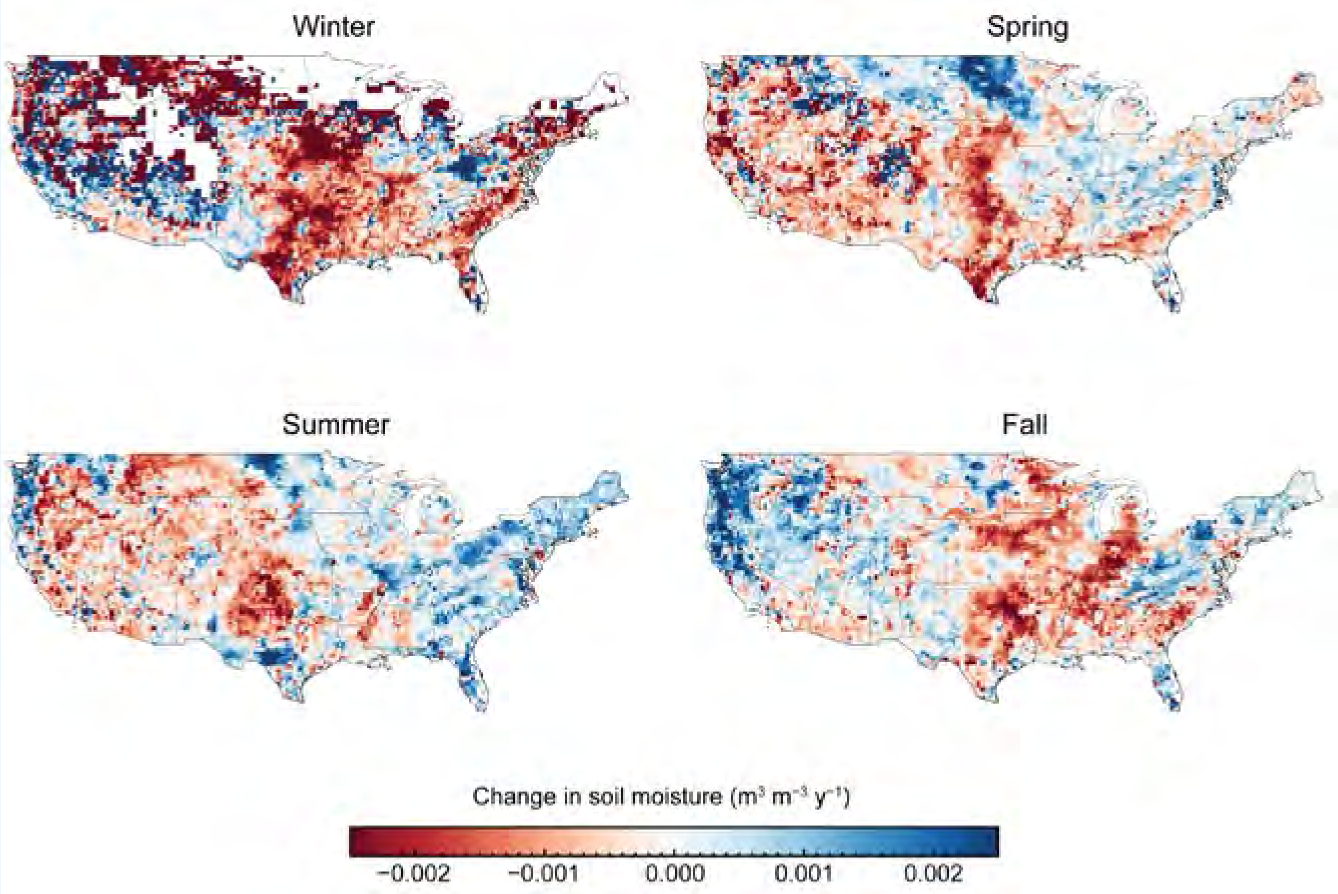


Figure 3.3. Changes in seasonal surface soil moisture per year over the period 1988 to 2010 based on multi-satellite datasets.[35] Seasonal drying is observed in central and lower Midwest and Southeast for most seasons (with the exception of the Southeast summer), and in most of the Southwest and West (with the exception of the Northwest) for spring and summer. Soil moisture in the upper Midwest, Northwest, and most of the Northeast is increasing in most seasons. (Images provided by W. Dorigo).

speed,[23,24] decreasing solar energy at the land surface due to increasing cloud cover and concentration of small particles (aerosols),[25] increasing humidity,[23] and declining soil moisture (Figure 3.2).[26]

Evapotranspiration projections vary by region,[27,28,29,30] but the atmospheric potential for ET is expected to increase; actual ET will be affected by regional soil moisture changes. Much more research is needed to confidently identify historical trends, causes, and implications for future ET trends.[31] This represents a critical uncertainty in projecting the impacts of climate change on regional water cycles.

Soil moisture plays a major role in the water cycle, regulating the exchange of water, energy, and carbon between the land surface and the atmosphere,[22] the production of runoff, and the recharge of groundwater aquifers. Soil moisture is projected to decline with higher temperatures and attendant increases in the potential for ET in much of the country, especially in the Great Plains,[29] Southwest,[18,32,33] and Southeast.[28,34]

Runoff and streamflow at regional scales declined during the last half-century in the Northwest.[36] Runoff and streamflow increased in the Mississippi Basin and Northeast, with no clear trends in much of the rest of the continental U.S.,[37] although a declining trend is emerging in annual runoff in the Colorado River Basin.[38] These changes need to be considered in the context of tree-ring studies in California's Central Valley, the Colorado River and Wind River basins, and the southeastern U.S. that indicate that these regions have experienced prolonged, even drier and wetter conditions at various times in the past two thousand years.[8,39,40] Human-caused climate change, when superimposed on past natural variability, may amplify these past extreme conditions. Projected changes in runoff for eight basins in the Northwest, northern Great Plains, and Southwest are illustrated in Figure 3.4.

Basins in the southwestern U.S. and southern Rockies (for example, the Rio Grande and Colorado River basins) are projected to experience gradual runoff declines during this century. Basins in the Northwest to north-central U.S. (for example, the

Streamflow Projections for River Basins in the Western U.S.

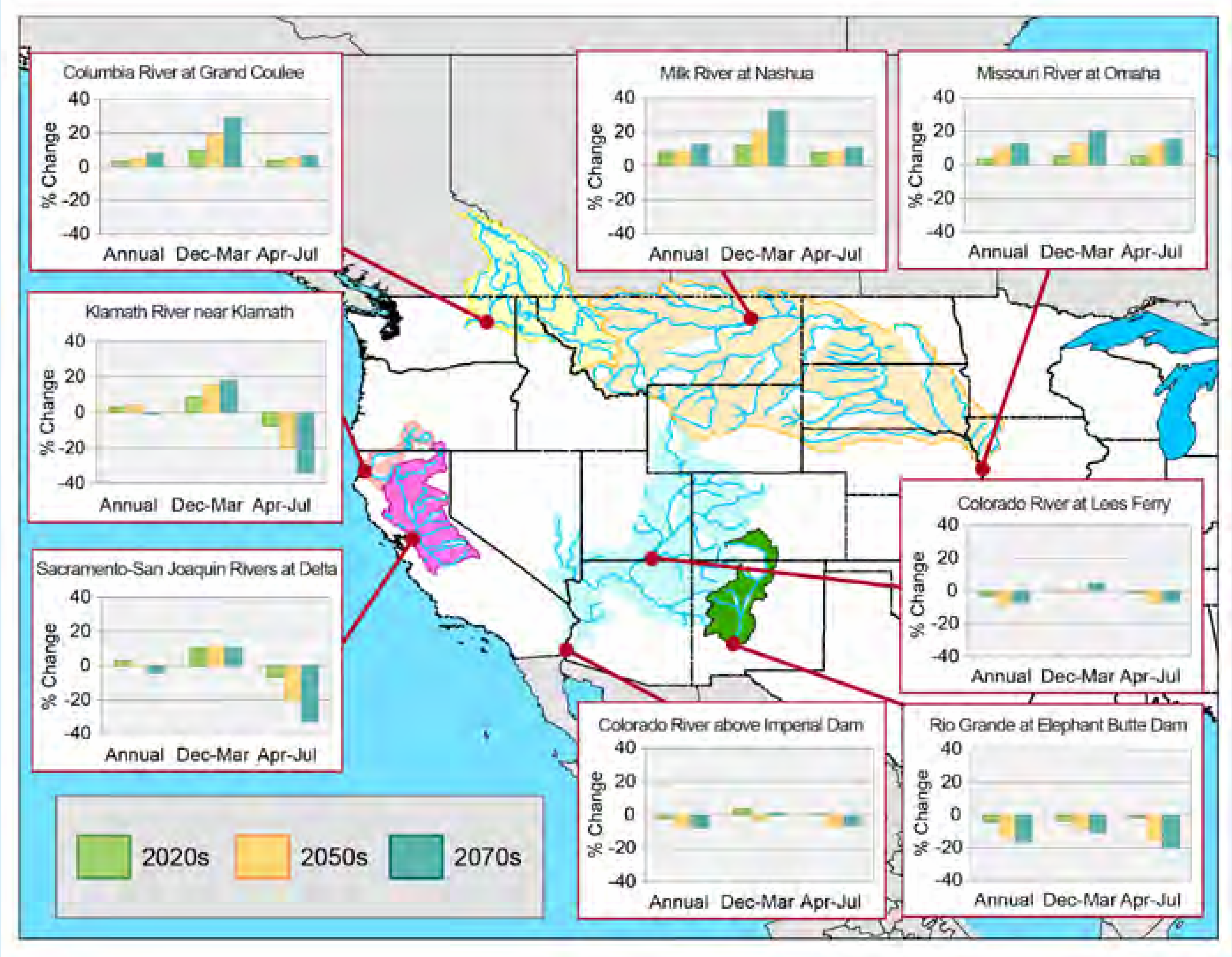


Figure 3.4. Annual and seasonal streamflow projections based on the B1 (with substantial emissions reductions), A1B (with gradual reductions from current emission trends beginning around mid-century), and A2 (with continuation of current rising emissions trends) CMIP3 scenarios for eight river basins in the western United States. The panels show percentage changes in average runoff, with projected increases above the zero line and decreases below. Projections are for annual, cool, and warm seasons, for three future decades (2020s, 2050s, and 2070s) relative to the 1990s. (Source: U.S. Department of the Interior – Bureau of Reclamation 2011;[41] Data provided by L. Brekke, S. Gangopadhyay, and T. Pruitt)

Columbia and the Missouri River basins) are projected to experience little change through the middle of this century, and increases by late this century.

Projected changes in runoff differ by season, with cool season runoff increasing over the west coast basins from California to Washington and over the north-central U.S. (for example, the San Joaquin, Sacramento, Klamath, Missouri, and Columbia River basins). Basins in the southwestern U.S. and southern Rockies are projected to see little change to slight decreases in the winter months.

Warm season runoff is projected to decrease substantially over a region spanning southern Oregon, the southwestern U.S., and southern Rockies (for example, the Klamath, Sacramento, San Joaquin, Rio Grande, and the Colorado River basins), and change little or increase slightly north of this region (for example, the Columbia and Missouri River basins).

In most of these western basins, these projected streamflow changes are outside the range of historical variability, especially by the 2050s and 2070s. The projected streamflow changes and associated uncertainties have water management implications (discussed below).

Key Message 2: Droughts Intensify

Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

Annual runoff and related river-flow are projected to decline in the Southwest[42,43] and Southeast,[34] and to increase in the Northeast, Alaska, Northwest, and upper Midwest regions,[42,43,44,45] broadly mirroring projected precipitation patterns.[46] Observational studies[47] have shown that decadal fluctuations in average temperature (up to 1.5°F) and precipitation changes of 10% have occurred in most areas of the U.S. during the last century. Fluctuations in river-flow indicate that effects of temperature are dominated by fluctuations in precipitation. Nevertheless, as warming affects water cycle processes, the amount of runoff generated by a given amount of precipitation is generally expected to decline.[37]

Droughts occur on time scales ranging from season-to-season to multiple years and even multiple decades. There has been no universal trend in the overall extent of drought across the continental U.S. since 1900. However, in the Southwest, widespread drought in the past decade has reflected both precipitation deficits and higher temperatures[8] in ways that resemble projected changes.[48] Long-term (multi-seasonal) drought conditions are also projected to increase in parts of the Southeast and possibly in Hawai'i and the Pacific Islands (Ch. 23: Hawai'i and Pacific Islands). Except in the few areas where increases in summer precipitation compensate, summer droughts (Ch. 2: Our Changing Climate) are expected to intensify almost everywhere in the continental U.S.[49] due to longer periods of dry weather and more extreme heat,[33] leading to more moisture loss from plants and earlier soil moisture depletion in basins where snowmelt shifts to earlier in the year.[50,51] Basins watered by glacial melt in the Sierra Nevada, Glacier National Park, and Alaska may experience increased summer river-flow in the next few decades, until the amounts of glacial ice become too small to contribute to river-flow.[52,53]

Key Message 3: Increased Risk of Flooding in Many Parts of the U.S.

Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.

There are various types of floods (see "Flood Factors and Flood Types"), some of which are projected to increase with continued climate change. Floods that are closely tied to heavy precipitation events, such as flash floods and urban floods, as well as coastal floods related to sea level rise and the resulting increase in storm surge height and inland impacts, are expected to increase. Other types of floods result from a more complex set of causes. For example, river floods are basin specific and dependent not only on precipitation but also on pre-existing soil moisture conditions, topography, and other factors, including important human-caused changes to watersheds and river courses across the United States.[54,55,56,57]

Significant changes in annual precipitation (Ch. 2: Our Changing Climate) and soil moisture (Figures 3.2 and 3.3), among other factors, are expected to affect annual flood magnitudes (Figure 3.5) in many regions.[58] River floods have been increasing in the Northeast and Midwest, and decreasing in the Southwest and Southeast.[56,57,58,59] These decreases are not surprising, as short duration very heavy precipitation events often occur during the summer and autumn when rivers are generally low. However, these very heavy precipitation events can and do lead to flash floods, often exacerbated in urban areas by the effect of impervious surfaces on runoff.

Heavy rainfall events are projected to increase, which is expected to increase the potential for flash flooding. Land cover, flow and water-supply management, soil moisture, and channel conditions are also important influences on flood generation[55] and must be considered in projections of future flood risks. Region-specific storm mechanisms and seasonality also affect flood peaks.[57] Because of this, and limited capacity to project future very heavy events with confidence, evaluations of the relative changes in various storm mechanisms may be useful.[57,60,61] Warming is likely to directly affect flooding in many mountain settings, as catchment areas receive increasingly more precipitation as rain rather than snow, or more rain falling on existing snowpack.[62] In some such settings, river flooding may increase as a result – even where precipitation and overall river flows decline (Ch. 2: Our Changing Climate).


Trends in Flood Magnitude

Figure 3.5. Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. Flooding in local areas can be affected by multiple factors, including land-use change, dams, and diversions of water for use. Most significant are increasing trends for floods in Midwest and Northeast, and a decreasing trend in the Southwest. (Figure source: Peterson et al. 2013[63]).

Key Message 4: Groundwater Availability

Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

Groundwater is the only perennial source of fresh water in many regions and provides a buffer against climate extremes. As such, it is essential to water supplies, food security, and ecosystems. Though groundwater occurs in most areas of the U.S., the capacity of aquifers to store water varies depending on the geology of the region. (Figure 3.6b illustrates the importance of groundwater aquifers.) In large regions of the Southwest, Great Plains, Midwest, Florida, and some other coastal areas, groundwater is the primary water supply. Groundwater aquifers in these areas are susceptible to the combined stresses of climate and water-use changes. For example, during the 2006–2009 California drought, when the source of irrigation shifted from surface water to predominantly groundwater, groundwater storage in California's Central Valley declined by an amount roughly equivalent to the storage capacity of Lake Mead, the largest reservoir in the United States.[64]

Climate change impacts on groundwater storage are expected to vary from place to place and aquifer to aquifer. Although precise responses of groundwater storage and flow to climate change are not well understood nor readily generalizable, recent and ongoing studies[65,66,67,68] provide insights on various underlying mechanisms:

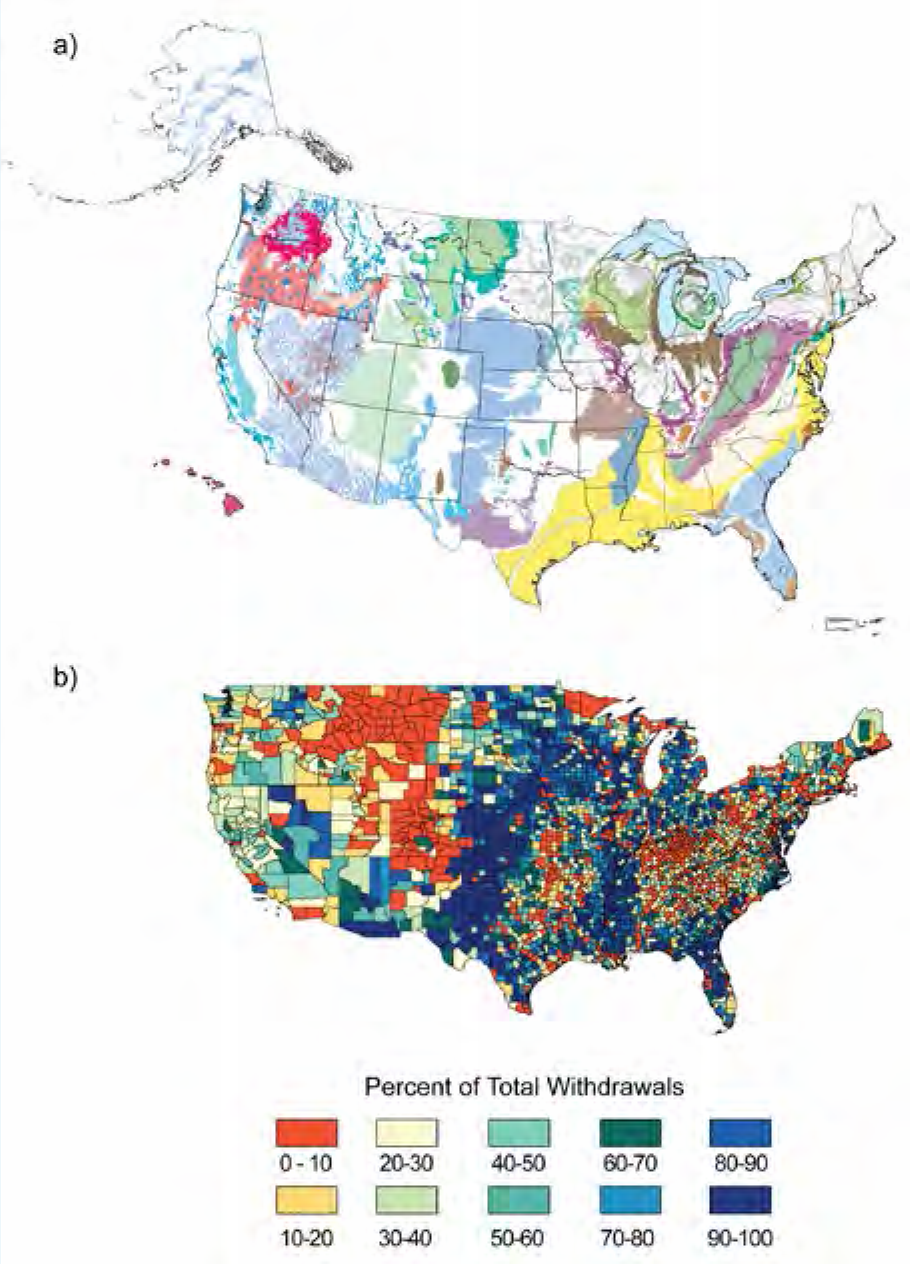
1) Precipitation is the key driver of aquifer recharge in water-limited environments (like arid regions), while evapotranspiration (ET) is the key driver in energy-limited environments (like swamps or marshlands).

2) Climate change impacts on aquifer recharge depend on several factors, including basin geology, frequency and intensity of high-rainfall periods that drive recharge, seasonal timing of recharge events, and strength of groundwater-surface water interaction.

3) Changes in recharge rates are amplified relative to changes in total precipitation, with greater amplification for drier areas.

With these insights in mind, it is clear that certain groundwater-dependent regions are projected to incur significant climate change related challenges. In some portions of the country, groundwater provides nearly 100% of the water supply (Figure 3.6b). Seasonal soil moisture changes are a key aquifer recharge driver and may provide an early indication of general aquifer recharge trends. Thus, the observed regional reductions in seasonal soil moisture for winter and spring (Figure 3.3) portend adverse recharge impacts for several U.S. regions, especially the Great Plains, Southwest, and Southeast.

Despite their critical national importance as water supply sources (see Figure 3.6), aquifers are not generally monitored



Principal U.S. Groundwater Aquifers and Use

Figure 3.6. (**a**) Groundwater aquifers are found throughout the U.S., but they vary widely in terms of ability to store and recharge water. The colors on this map illustrate aquifer location and geology: blue colors indicate unconsolidated sand and gravel; yellow is semi-consolidated sand; green is sandstone; blue or purple is sandstone and carbonate-rock; browns are carbonate-rock; red is igneous and metamorphic rock; and white is other aquifer types. (Figure source: USGS). (**b**) Ratio of groundwater withdrawals to total water withdrawals from all surface and groundwater sources by county. The map illustrates that aquifers are the main (and often exclusive) water supply source for many U.S. regions, especially in the Great Plains, Missssissippi Valley, east central U.S., Great Lakes region, Florida, and other coastal areas. Groundwater aquifers in these regions are prone to impacts due to combined climate and water-use change. (Data from USGS 2005).

in ways that allow for clear identification of climatic influences on groundwater recharge, storage, flows, and discharge. Nearly all monitoring is focused in areas and aquifers where variations are dominated by groundwater pumping, which largely masks climatic influences,[69] highlighting the need for a national framework for groundwater monitoring.[70]

Generally, impacts of changing demands on groundwater systems, whether due directly to climate changes or indirectly through changes in land use or surface-water availability and management, are likely to have the most immediate effects on groundwater availability;[67,71] changes in recharge and storage may be more subtle and take longer to emerge. Groundwater models have only recently begun to include detailed representations of groundwater recharge and interactions with surface-water and land-surface processes,[50] with few projections of groundwater responses to climate change.[68,72] However, surface water declines have already resulted in larger groundwater withdrawals in some areas (for example, in the Central Valley of California and in the Southeast) and may be aggravated by climate change challenges.[73] In many mountainous areas of the U.S., groundwater recharge is disproportionately generated from snowmelt infiltration, suggesting that the loss of snowpack will affect recharge rates and patterns.[50,51,66,74] Models do not yet include dynamic representations of the groundwater reservoir and its connections to streams, the soil-vegetation system, and the atmosphere, limiting the understanding of the potential climate change impacts on groundwater and groundwater-reliant systems.[75]

As the risk of drought increases, groundwater can play a key role in enabling adaptation to climate variability and change. For example, groundwater can be augmented by surface water during times of high flow through aquifer recharge strategies, such as infiltration basins and injection wells. In addition, management strategies can be implemented that use surface water for irrigation and water supply during wet periods, and groundwater during drought, although these approaches face practical limitations within current management and institutional frameworks.[71,76]

Key Message 5: Risks to Coastal Aquifers and Wetlands

Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

With more than 50% of the nation's population concentrated near coasts (Chapter 25: Coasts),[77] coastal aquifers and wetlands are precious resources. These aquifers and wetlands, which are extremely important from a biological/biodiversity perspective (see Ch. 8: Ecosystems; Ch. 25: Coasts), may be particularly at risk due to the combined effects of inland droughts and floods, increased surface water impoundments and diversions, increased groundwater withdrawals, and accelerating sea level rise and greater storm surges.[78,79] Estuaries are particularly vulnerable to changes in freshwater inflow and sea level rise by changing salinity and habitat of these areas.

Several coastal areas, including the Delaware, Susquehanna, and Potomac River deltas on the Northeast seaboard, most of Florida, the Apalachicola and Mobile River deltas and bays, the Mississippi River delta in Louisiana, and the delta of the Sacramento-San Joaquin rivers in northern California, are particularly vulnerable due to the combined effects of climate change and other human-caused stresses. In response, some coastal communities are among the nation's most proactive in adaptation planning (Chapter 25: Coasts).

Key Message 6: Water Quality Risks to Lakes and Rivers

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.

Water temperature has been increasing in some rivers.[80] The length of the season that lakes and reservoirs are thermally stratified (with separate density layers) is increasing with increased air and water temperatures.[81,82] In some cases, seasonal mixing may be eliminated in shallow lakes, decreasing dissolved oxygen and leading to excess concentrations of nutrients (nitrogen and phosphorous), heavy metals (such as mercury), and other toxins in lake waters.[81,82]

Lower and more persistent low flows under drought conditions as well as higher flows during floods can worsen water quality. Increasing precipitation intensity, along with the effects of wildfires and fertilizer use, are increasing sediment, nutrient, and contaminant loads in surface waters used by downstream water users[84] and ecosystems. Mineral weathering products, like calcium, magnesium, sodium, and silicon and nitrogen loads[85] have been increasing with higher streamflows.[86] Changing land cover, flood frequencies, and flood magnitudes are expected to increase mobilization of sediments in large river basins.[87]

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease water quality in many ways. Here, middle school students in Colorado learn about water quality.

Changes in sediment transport are expected to vary regionally and by land-use type, with potentially large increases in some areas,[88] resulting in alterations to reservoir storage and river channels, affecting flooding, navigation, water supply, and dredging. Increased frequency and duration of droughts, and associated low water levels, increase nutrient concentrations and residence times in streams, potentially increasing the likelihood of harmful algal blooms and low oxygen conditions.[89] Concerns over such impacts and their potential link to climate change are rising for many U.S. regions including the Great Lakes,[90] Chesapeake Bay,[91] and the Gulf of Mexico.[85,86] Strategies aiming to reduce sediment, nutrient, and contaminant loads at the source remain the most effective management responses.[92]

Observed Changes in Lake Stratification and Ice Covered Area

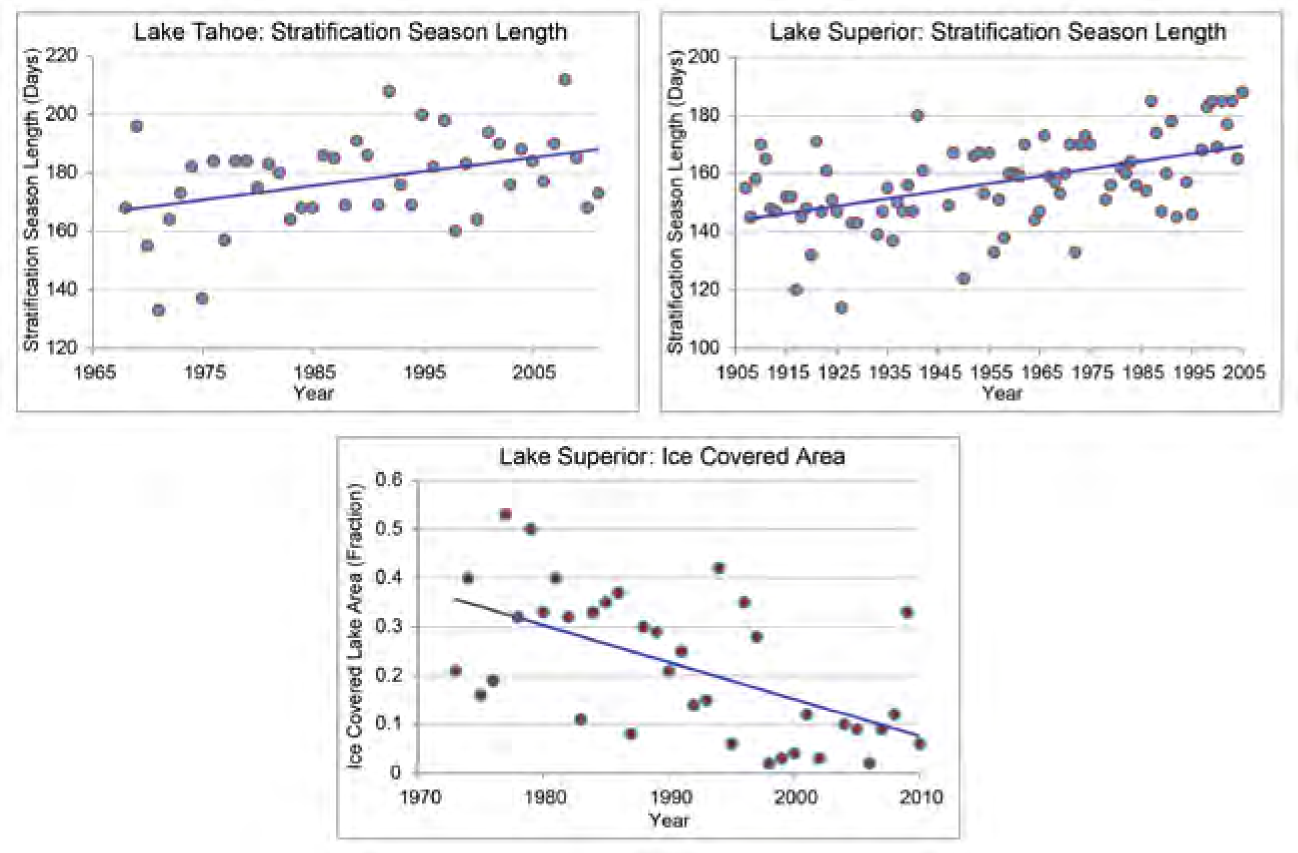


Figure 3.7. The length of the season in which differences in lake temperatures with depth cause stratification (separate density layers) is increasing in many lakes. In this case, measurements show stratification has been increasing in Lake Tahoe (top left) since the 1960s and in Lake Superior (top right) since the early 1900s in response to increasing air and surface water temperatures (see also Ch. 18: Midwest). In Lake Tahoe, because of its large size (relative to inflow) and resulting long water-residence times, other influences on stratification have been largely overwhelmed, and warming air and water temperatures have caused progressive declines in near-surface density, leading to longer stratification seasons (by an average of 20 days), decreasing the opportunities for deep lake mixing, reducing oxygen levels, and causing impacts to many species and numerous aspects of aquatic ecosystems.[83] Similar effects are observed in Lake Superior,[16] where the stratification season is lengthening (top right) and annual ice-covered area is declining (bottom); both observed changes are consistent with increasing air and water temperatures.

Relationship between Historical and Projected Water Cycle Changes

Natural climate variations occur on essentially all time scales from days to millennia, and the water cycle varies in much the same way. Observations of changes in the water cycle over time include responses to natural hydroclimatic variability as well as other, more local, human influences (like dam building or land-use changes), or combinations of these influences with human-caused climate change. Some recent studies have attributed specific observed changes in the water cycle to human-induced climate change (for example, Barnett et al. 2008[10]). For many other water cycle variables and impacts, the observed and projected responses are consistent with those expected by human-induced climate change and other human influences. Research aiming to formally attribute these responses to their underlying causes is ongoing.

FLOOD FACTORS AND FLOOD TYPES

A flood is defined as any high flow, overflow, or inundation by water that causes or threatens damage.[93] Floods are caused or amplified by both weather- and human-related factors. Major weather factors include heavy or prolonged precipitation, snowmelt, thunderstorms, storm surges from hurricanes, and ice or debris jams. Human factors include structural failures of dams and levees, inadequate drainage, and land cover alterations (such as pavement or deforestation) that reduce the capacity of the land surface to absorb water. Increasingly, humanity is also adding to weather-related factors, as human-induced warming increases heavy downpours, causes more extensive storm surges due to sea level rise, and leads to more rapid spring snowmelt.

Worldwide, from 1980 to 2009, floods caused more than 500,000 deaths and affected more than 2.8 billion people.[94] In the U.S., floods caused 4,586 deaths from 1959 to 2005[95] while property and crop damage averaged nearly $8 billion per year (in 2011 dollars) over 1981 through 2011.[93] The risks from future floods are significant, given expanded development in coastal areas and floodplains, unabated urbanization, land-use changes, and human-induced climate change.[94]

Major flood types include flash, urban, riverine, and coastal flooding:

Flash floods occur in small and steep watersheds and waterways and can be caused by short-duration intense precipitation, dam or levee failure, or collapse of debris and ice jams. Snow cover and frozen ground conditions can exacerbate flash flooding during winter and early spring by increasing the fraction of precipitation that runs off. Flash floods develop within minutes or hours of the causative event, and can result in severe damage and loss of life due to high water velocity, heavy debris load, and limited warning. Most flood-related deaths in the U.S. are associated with flash floods.

Flash Flooding: Cave Creek, Arizona (Photo credit: Tom McGuire).

Urban flooding can be caused by short-duration very heavy precipitation. Urbanization creates large areas of impervious surfaces (such as roads, pavement, parking lots, and buildings) and increases immediate runoff. Stormwater drainage removes excess surface water as quickly as possible, but heavy downpours can exceed the capacity of drains and cause urban flooding.

Flash floods and urban flooding are directly linked to heavy precipitation and are expected to increase as a result of projected increases in heavy precipitation events. In mountainous watersheds, such increases may be partially offset in winter and spring due to projected snowpack reduction.

Riverine Flooding: In many regions, infrastructure is currently vulnerable to flooding, as demonstrated in these photos. Left: The Fort Calhoun Nuclear Power Plant in eastern Nebraska was surrounded by a Missouri River flood on June 8, 2011, that also affected Louisiana, Mississippi, Missouri, Illinois, Kentucky, Tennessee, and Arkansas (photo credit: Larry Geiger). Right: The R.M. Clayton sewage treatment plant in Atlanta, Georgia, September 23, 2009, was engulfed by floodwaters forcing it to shut down and resulting in the discharge of raw sewage into the Chattahoochee River (photo credit: Reuters/David Tulis). Flooding also disrupts road and rail transportation, and inland navigation.

Riverine flooding occurs when surface water drains from a watershed into a stream or a river exceeds channel capacity, overflows the

Continued

FLOOD FACTORS AND FLOOD TYPES (CONTINUED)

banks, and inundates adjacent low lying areas. Riverine flooding is commonly associated with large watersheds and rivers, while flash and urban flooding occurs in smaller natural or urban watersheds. Because heavy precipitation is often localized, riverine flooding typically results from multiple heavy precipitation events over periods of several days, weeks, or even months. In large basins, existing soil moisture conditions and evapotranspiration rates also influence the onset and severity of flooding, as runoff increases with wetter soil and/or lower evapotranspiration conditions. Snow cover and frozen ground conditions can also exacerbate riverine flooding during winter and spring by increasing runoff associated with rain-on-snow events and by snowmelt, although these effects may diminish in the long term as snow accumulation decreases due to warming. Since riverine flooding depends on precipitation as well as many other factors, projections about changes in frequency or intensity are more uncertain than with flash and urban flooding.

Coastal flooding is predominantly caused by storm surges that accompany hurricanes and other storms. Low storm pressure creates strong winds that create and push large sea water domes, often many miles across, toward the shore. The approaching domes can raise the water surface above normal tide levels (storm surge) by more than 25 feet, depending on various storm and shoreline factors. Inundation, battering waves, and floating debris associated with storm surge can cause deaths, widespread infrastructure damage (to buildings, roads, bridges, marinas, piers, boardwalks, and sea walls), and severe beach erosion. Storm-related rainfall can also cause inland flooding (flash, urban, or riverine) if, after landfall, the storm moves slowly or stalls over an area. Inland flooding can occur close to the shore or hundreds of miles away and is responsible for more than half of the deaths associated with tropical storms.[93] Climate change affects coastal flooding through sea level rise and storm surge, increases in heavy rainfall during hurricanes and other storms, and related increases in flooding in coastal rivers.

Hurricane Sandy coastal flooding in Mantoloking, N.J. (Photo credit: New Jersey National Guard/Scott Anema).

In some locations, early warning systems have helped reduce deaths, although property damage remains considerable (Ch. 28: Adaptation). Further improvements can be made by more effective communication strategies and better land-use planning.[94]

Climate Change Impacts on Water Resource Uses and Management

People use water for many different purposes and benefits. Our water use falls into five main categories: 1) municipal use, which includes domestic water for drinking and bathing; 2) agricultural use, which includes irrigation and cattle operations; 3) industrial use, which includes electricity production from coal- or gas-fired power plants that require water to keep the machinery cool; 4) providing ecosystem benefits, such as supporting the water needs of plants and animals we depend on; and 5) recreational uses, such as boating and fishing.

Water is supplied for these many uses from two main sources:

- freshwater withdrawals (from streams, rivers, lakes, and aquifers), which supply water for municipal, industrial, agricultural, and recirculating thermoelectric plant cooling water supply;

- instream surface water flows, which support hydropower production, once-through thermoelectric plant cooling, navigation, recreation, and healthy ecosystems.

Key Message 7: Changes to Water Demand and Use

Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.

Climate change, acting concurrently with demographic, land-use, energy generation and use, and socioeconomic changes, is challenging existing water management practices by affecting water availability and demand and by exacerbating competition among uses and users (see Ch. 4: Energy; Ch. 6: Agriculture; Ch. 10: Energy, Water, and Land; Ch. 12: Indigenous Peoples; and Ch. 13: Land Use & Land Cover Change). In some regions, these current and expected impacts are hastening efficiency improvements in water withdrawal and use, the deployment of more proactive water management and adaptation approaches, and the reassessment of the water infrastructure and institutional responses.[1]

Water Withdrawals

Total freshwater withdrawals (including water that is withdrawn and consumed as well as water that returns to the original source) and consumptive uses have leveled off nationally since 1980 at 350 billion gallons of withdrawn water and 100 billion gallons of consumptive water per day, despite the addition of 68 million people from 1980 to 2005 (Figure 3.8).[96] Irrigation and all electric power plant cooling withdrawals account for approximately 77% of total withdrawals, municipal and industrial for 20%, and livestock and aquaculture for 3%. Most thermoelectric withdrawals are returned back to rivers after cooling, while most irrigation withdrawals are consumed by the processes of evapotranspiration and plant growth. Thus, consumptive water use is dominated by irrigation (81%) followed distantly by municipal and industrial (8%) and the remaining water uses (5%). See Figure 3.9.

Water sector withdrawals and uses vary significantly by region. There is a notable east-west water use pattern, with the largest regional withdrawals occurring in western states (where the climate is drier) for agricultural irrigation (Figure 3.10a,d). In the east, water withdrawals mainly serve municipal, industrial, and thermoelectric uses (Figure 3.10a,b,c). Irrigation is also dominant along the Mississippi Valley, in Florida, and in southeastern Texas. Groundwater withdrawals are especially intense in parts of the Southwest, Southeast, Northwest, and

U.S. Freshwater Withdrawal, Consumptive Use, and Population Trends

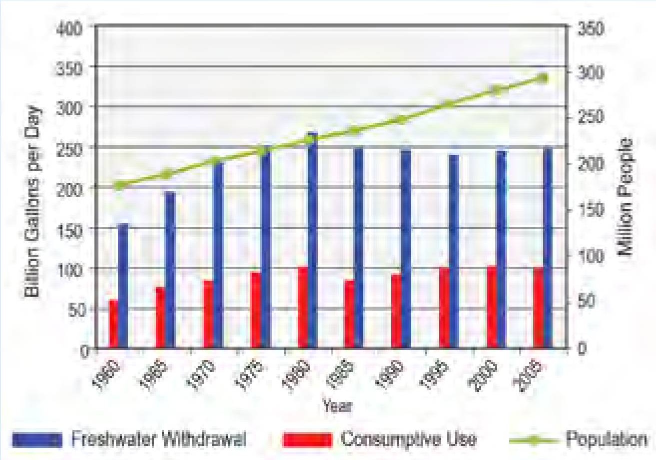


Figure 3.8. Trends in total freshwater withdrawal (equal to the sum of consumptive use and return flows to rivers) and population in the contiguous United States. This graph illustrates the remarkable change in the relationship between water use and population growth since about 1980. Reductions in per capita water withdrawals are directly related to increases in irrigation efficiency for agriculture, more efficient cooling processes in electrical generation, and, in many areas, price signals, more efficient indoor plumbing fixtures and appliances, and reductions in exterior landscape watering, in addition to shifts in land-use patterns in some areas.[97] Efficiency improvements have offset the demands of a growing population and have resulted in more flexibility in meeting water demand. In some cases these improvements have also reduced the flexibility to scale back water use in times of drought because some inefficiencies have already been removed from the system. With drought stress projected to increase in many U.S. regions, drought vulnerability is also expected to rise.[1]

Freshwater Withdrawals by Sector

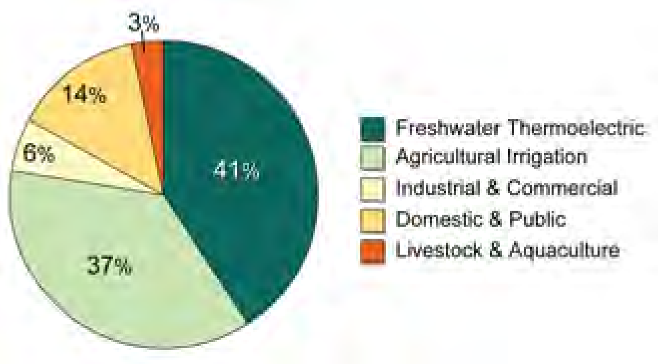


Figure 3.9. Total water withdrawals (groundwater and surface water) in the U.S. are dominated by agriculture and energy production, though the primary use of water for thermoelectric production is for cooling, where water is often returned to lakes and rivers after use (return flows). (Data from Kenny et al. 2009[96])

U.S. Water Withdrawal Distribution

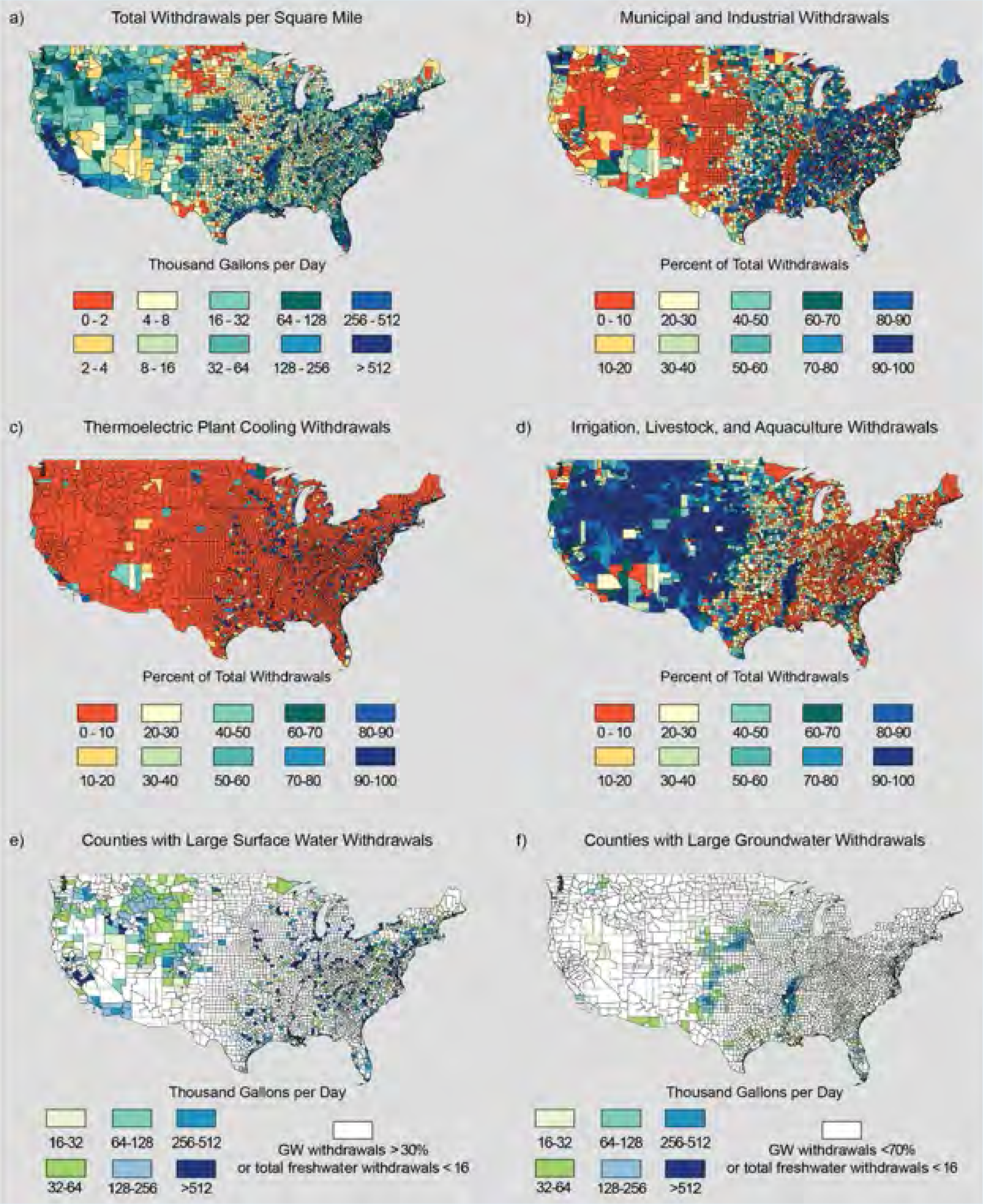


Figure 3.10. Based on the most recent USGS water withdrawal data (2005). This figure illustrates water withdrawals at the U.S. county level: (a) total withdrawals (surface and groundwater) in thousands of gallons per day per square mile; (b) municipal and industrial (including golf course irrigation) withdrawals as percent of total; (c) irrigation, livestock, and aquaculture withdrawals as percent of total; (d) thermoelectric plant cooling withdrawals as percent of total; (e) counties with large surface water withdrawals; and (f) counties with large groundwater withdrawals. The largest withdrawals occur in the drier western states for crop irrigation. In the east, water withdrawals mainly serve municipal, industrial, and thermoelectric uses. Groundwater withdrawals are intense in parts of the Southwest and Northwest, the Great Plains, Mississippi Valley, Florida and South Georgia, and near the Great Lakes (Figure source: Georgia Water Resources Institute, Georgia Institute of Technology; Data from Kenny et al. 2009;[96] USGS 2013[98]).

Great Plains, the Mississippi Valley, Florida and South Georgia, and near the Great Lakes (Figure 3.10f). Surface waters are most intensely used in all other U.S. regions.

Per capita water withdrawal and use are decreasing due to many factors.[99] These include demand management, new plumbing codes, water-efficient appliances, efficiency improvement programs, and pricing strategies, especially in the municipal sector.[100] Other factors contributing to decreasing per capita water use include changes from water-intensive manufacturing and other heavy industrial activities to service-oriented businesses,[101] and enhanced water-use efficiencies in response to environmental pollution legislation (in the industrial and commercial sector). In addition, replacement of older once-through-cooling electric power plants by plants that recycle their cooling water, and switching from flood irrigation to more efficient methods in the western United States[102] have also contributed to these trends.

Notwithstanding the overall national trends, regional water withdrawal and use are strongly correlated with climate;[103] hotter and drier regions tend to have higher per capita usage, and water demand is affected by both temperature and precipitation on a seasonal basis (see also Ch. 28: Adaptation).

Water demand is projected to increase as population grows, and will increase substantially more in some regions as a result of climate change. In the absence of climate change but in response to a projected population increase of 80% and a 245% increase in total personal income from 2005 to 2060, simulations under the A1B scenario indicate that total water demand in the U.S. would increase by 3%.[99] Under these conditions, approximately half of the U.S. regions would experience an overall decrease in water demand, while the other half would experience an increase (Figure 3.11a). If, however, climate change projections based on the A1B emissions scenario (with gradual reductions from current emission trends beginning around mid-century) and three climate models are also factored in, the total water demand is projected to rise by an average of 26% over the same period (Figure 3.11b).[99] Under the population increase scenario that also includes climate change, 90% of the country is projected to experience a total demand increase, with decreases projected only in parts of the Midwest, Northeast and Southeast. Compared to an 8% increase in demand under a scenario without climate change, projections under the A2 emissions scenario (which assumes continued increases in global emissions) and three climate models over the 2005 to 2060 period result in a 34% increase in total water demand. By 2090, total water demand is projected to increase by 42% over 2005 levels under the A1B scenario and 82% under the higher A2 emissions scenario.

Crop irrigation and landscape watering needs are directly affected by climate change, especially by projected changes in temperature, potential evapotranspiration, and soil moisture. Consequently, the projected climate change impacts on water demand are larger in the western states, where irrigation dominates total water withdrawals (see Figure 3.10). Uncertainties in the projections of these climate variables also affect water demand projections.[99] However, it is clear that the impacts of projected population, socioeconomic, and climate changes amplify the effects on water demand in the Southwest and Southeast, where the observed and projected drying water cycle trends already make these regions particularly vulnerable.

This vulnerability will be exacerbated by physical and operational limitations of water storage and distribution systems. River reservoirs and associated dams are usually designed to handle larger-than-historical streamflow variability ranges. Some operating rules and procedures reflect historical seasonal and interannual streamflow and water release patterns, while others include information about current and near-term conditions, such as snowpack depth and expected snowmelt volume. Climate change threatens to alter both the streamflow variability that these structures must accommodate and their opportunities to recover after doing so (due to permanent changes in average streamflow). Thus, as streamflow and demand patterns change, historically based operating rules and procedures could become less effective in balancing water supply with other uses.[104]

Some of the highest water demand increases under climate change are projected in U.S. regions where groundwater aquifers are the main water supply source (Figure 3.11b), including the Great Plains and parts of the Southwest and Southeast. The projected water demand increases combined with potentially declining recharge rates (see water cycle section) further challenge the sustainability of the aquifers in these regions.

Power plant cooling is a critical national water use, because nearly 90% of the U.S. electrical energy is produced by thermoelectric power plants.[105] Freshwater withdrawals per kilowatt hour have been falling in recent years due to the gradual replacement of once-through cooling of power plant towers with plants that recycle cooling water. Thermal plant cooling is principally supported by surface water withdrawals (Figure 3.10e,f) and has already been affected by climate change in areas where temperatures are increasing and surface water supplies are diminishing, such as the southern United States. Higher water temperatures affect the efficiency of electric generation and cooling processes. It also limits the ability of utilities to discharge heated water to streams from once-through cooled power systems due to regulatory requirements and concerns about how the release of warmer water into rivers and streams affects ecosystems and biodiversity (see Ch. 4: Energy).[106]

Projected Changes in Water Withdrawals

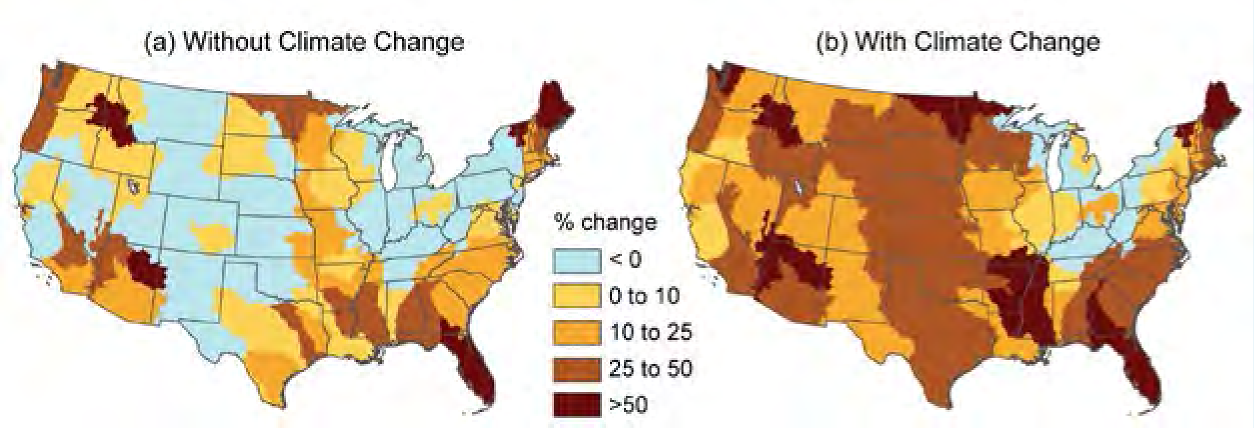


Figure 3.11. The effects of climate change, primarily associated with increasing temperatures and potential evapotranspiration, are projected to significantly increase water demand across most of the United States. Maps show percent change from 2005 to 2060 in projected demand for water assuming (a) change in population and socioeconomic conditions based on the underlying A1B emissions scenario, but with no change in climate, and (b) combined changes in population, socioeconomic conditions, and climate according to the A1B emissions scenario (gradual reductions from current emission trends beginning around mid-century). (Figure source: Brown et al. 2013[99]).

Instream Water Uses

Hydropower contributes 7% of electricity generation nationwide, but provides up to 70% in the Northwest and 20% in California, Alaska, and the Northeast.[107] Climate change is expected to affect hydropower directly through changes in runoff (average, extremes, and seasonality), and indirectly through increased competition with other water uses. Based on runoff projections, hydropower is expected to decline in the southern U.S. (especially the Southwest) and increase in the Northeast and Midwest (though actual gains or losses will depend on facility size and changes in runoff volume and timing). Where non-power water demands are expected to increase (as in the southern U.S.), hydropower generation, dependable capacity, and ancillary services are likely to decrease. Many hydropower facilities nationwide, especially in the Southeast, Southwest, and the Great Plains, are expected to face water availability constraints.[108] While some hydropower facilities may face water-related limitations, these could be offset to some degree by the use of more efficient turbines as well as innovative new hydropower technologies.

Inland navigation, most notably in the Great Lakes and the Missouri, Mississippi, and Ohio River systems, is particularly important for agricultural commodities (transported from the Midwest to the Gulf Coast and on to global food markets), coal, and iron ore.[1,109] Navigation is affected by ice cover and by floods and droughts. Seasonal ice cover on the Great Lakes has been decreasing[16] which may allow increased shipping.[110] However, lake level declines are also possible in the long term, decreasing vessel draft and cargo capacity. Future lake levels may also depend on non-climate factors and are uncertain both in direction and magnitude (see Ch. 2: Our Changing Climate; Ch. 5: Transportation; and Ch. 18: Midwest). Similarly, although the river ice cover period has been decreasing[53] (extending the inland navigation season), seasonal ice cover changes[111,112] could impede lock operations.[112] Intensified floods are likely to hinder shipping by causing waterway closures and damaging or destroying ports and locks. Droughts have already been shown to decrease reliability of flows or channel depth, adversely impacting navigation (Ch. 5: Transportation). Both floods and droughts can disrupt rail and road traffic and increase shipping costs[113] and result in commodity price volatility (Ch. 19: Great Plains).

Recreational activities associated with water resources, including boating, fishing, swimming, skiing, camping, and wildlife watching, are strong regional and national economic drivers.[114] Recreation is sensitive to weather and climate,[115] and climate change impacts to recreation can be difficult to project.[116] Rising temperatures affect extent of snowcover and mountain snowpack, with impacts on skiing[117] and snowmobiling.[118] As the climate warms, changes in precipitation and runoff are expected to result in both beneficial (in some regions) and adverse impacts[115] to water sports, with potential for considerable economic dislocation and job losses.[118]

Changing climate conditions are projected to affect water and wastewater treatment and disposal in ways that depend on system-specific and interacting attributes. For example, elevated stream temperatures, combined with lower flows, may require wastewater facilities to increase treatment to meet stream water quality standards.[119] More intense precipitation and floods, combined with escalating urbanization and associated increasing impermeable surfaces, may amplify the likelihood of contaminated overland flow or combined sewer overflows.[120] Moderate precipitation increases, however, could result in increased stream flows, improving capacity to dilute contaminants in some regions. Sea level rise and more frequent coastal flooding could damage wastewater utility infrastructure and reduce treatment efficiency (Ch. 25: Coasts).[121]

Changes in streamflow temperature and flow regimes can affect aquatic ecosystem structure and function (see Ch. 8: Ecosystems). Water temperature directly regulates the physiology, metabolism, and energy of individual aquatic organisms, as well as entire ecosystems. Streamflow quantity influences the extent of available aquatic habitats, and streamflow variability regulates species abundance and persistence. Flow also influences water temperature, sediment, and nutrient concentrations.[122] If the rate of climate change[123] outpaces plant and animal species' ability to adjust to temperature change, additional biodiversity loss may occur. Furthermore, climate change induced water cycle alterations may exacerbate existing ecosystem vulnerability, especially in the western United States[124] where droughts and water shortages are likely to increase. But areas projected to receive additional precipitation, such as the northern Great Plains, may benefit. Lastly, hydrologic alterations due to human interventions have without doubt impaired riverine ecosystems in most U.S. regions and globally.[125] The projected escalation of water withdrawals and uses (see Figure 3.11) threatens to deepen and widen ecosystem impairment, especially in southern states where climate change induced water cycle alterations are pointing toward drier conditions (see Ch. 8: Ecosystems). In these regions, balancing socioeconomic and environmental objectives will most likely require more deliberate management and institutional responses.

Major Water Resource Vulnerabilities and Challenges

Many U.S. regions are expected to face increased drought and flood vulnerabilities and exacerbated water management challenges. This section highlights regions where such issues are expected to be particularly intense.

Key Message 8: Drought is Affecting Water Supplies

Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.

Many southwestern and western watersheds, including the Colorado, Rio Grande,[38,43,126] and Sacramento-San Joaquin,[127,128] have recently experienced drier conditions. Even larger runoff reductions (about 10% to 20%) are projected over some of these watersheds in the next 50 years.[48,129] Increasing evaporative losses, declining runoff and groundwater recharge, and changing groundwater pumpage are expected to affect surface and groundwater supplies[65,66,67,71] and increase the risk of water shortages for many water uses. Changes in streamflow timing will exacerbate a growing mismatch between supply and demand (because peak flows are occurring earlier in the spring, while demand is highest in mid-summer) and will present challenges for the management of reservoirs, aquifers, and other water infrastructure.[130] Rising stream temperatures and longer low flow periods may make electric power plant cooling water withdrawals unreliable, and may affect aquatic and riparian ecosystems by degrading habitats and favoring invasive, non-native species.[131]

Key Message 9: Flood Effects on People and Communities

Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

Flooding affects critical water, wastewater, power, transportation, and communications infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (see "Flood Factors and Flood Types"). Very heavy precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Increasing heavy precipitation is an important contributing factor, but flood magnitude changes also depend on specific watershed conditions (including soil moisture, impervious area, and other human-caused alterations).

Projected changes in flood frequency based on climate projections and hydrologic models have recently begun to emerge (for example, Das et al. 2012;[60] Brekke et al. 2009;[132] Raff et al. 2009;[133] Shaw and Riha 2011;[134] Walker et al. 2011[135]), and suggest that flood frequency and severity increases may occur in the Northeast and Midwest (Ch. 16: Northeast; Ch. 18: Midwest). Flooding and sea water intrusion from sea level rise and increasing storm surge threaten New York, Boston, Philadelphia, Virginia Beach, Wilmington, Charleston, Miami, Tampa, Naples, Mobile, Houston, New Orleans, and many other cities on U.S. coasts (Chapter 25: Coasts).

The devastating toll of large floods (human life, property, environment, and infrastructure) suggests that proactive management measures could minimize changing future flood risks and consequences (Ch. 28: Adaptation). In coastal areas, sea level rise may act in parallel with inland climate changes to intensify water-use impacts and challenges (Ch. 12: Indigenous Peoples; Ch. 17: Southeast).[136] Increasing flooding risk, both coastal and inland, could also exacerbate human health risks associated with failure of critical infrastructure,[137,138] and an increase in both waterborne diseases (Ch. 9: Human Health)[139] and airborne diseases.[140]

Changes in land use, land cover, development, and population distribution can all affect flood frequency and intensity. The nature and extent of these projected changes results in increased uncertainty and decreased accuracy of flood forecasting in both the short term[133] and long term.[141] This lack of certainty could hinder effective preparedness (such as evacuation planning) and the effectiveness of structural and non-structural flood risk reduction measures. However, many climate change projections are robust (Ch. 2: Our Changing Climate), and the long lead time needed for the planning, design, and construction of critical infrastructure that provides resilience to floods means that consideration of long-term changes is needed.

Effective climate change adaptation planning requires an integrated approach[45,118,142] that addresses public health and safety issues (Ch. 28: Adaptation).[143] Though numerous flood risk reduction measures are possible, including levees, land-use zoning, flood insurance, and restoration of natural floodplain retention capacity,[144] economic and institutional conditions may constrain implementation. The effective use of these measures would require significant investment in many cases,[145] as well as updating policies and methods to account for climate change[42,146] in the planning, design, operation, and maintenance of flood risk reduction infrastructure.[132,147]

Adaptation and Institutional Responses

Key Message 10: Water Resources Management

In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.

Water managers and planners strive to balance water supply and demand across all water uses and users. The management process involves complex tradeoffs among water-use benefits, consequences, and risks. By altering water availability and demand, climate change is likely to present additional management challenges. One example is in the Sacramento-San Joaquin River Delta, where flooding, sea water intrusion, and changing needs for environmental, municipal, and agricultural water uses have created significant management challenges. This California Bay-Delta experience suggests that managing risks and sharing benefits requires re-assessment of very complex ecosystems, infrastructure systems, water rights, stakeholder preferences, and reservoir operation strategies – as well as significant investments. All of these considerations are subject to large uncertainties.[54,148] To some extent, all U.S. regions are susceptible, but the Southeast and Southwest are highly vulnerable because climate change is projected to reduce water availability, increase demand, and exacerbate shortages (see “Water Management”).

Recent assessments illustrate water management challenges facing California,[127,129,149,150] the Southwest,[130,151] Southeast (Ch. 17: Southeast),[136,152] Northwest,[153] Great Plains,[154] and Great Lakes.[155] A number of these assessments demonstrate that while expanding supplies and storage may still be possible in some regions, effective climate adaptation strategies can benefit from innovative management strategies. These strategies can include domestic water conservation programs that use pricing incentives to curb use; more flexible, risk-based, better-informed, and adaptive operating rules for reservoirs; the integrated use of combined surface and groundwater resources; and better monitoring and assessment of statewide water use.[129,149,156,157] Water management and planning would benefit from better coordination among public sectors at the national, state, and local levels (including regional partnerships and agreements), and the private sector, with participation of all relevant stakeholders in well-informed, fair, and equitable decision-making processes. Better coordination among hydrologists and atmospheric scientists, and among these scientists and the professional water management community, is also needed to facilitate more effective translation of knowledge from science to practice (Ch. 26: Decision Support; Ch. 28: Adaptation).[158]

WATER CHALLENGES IN A SOUTHEAST RIVER BASIN

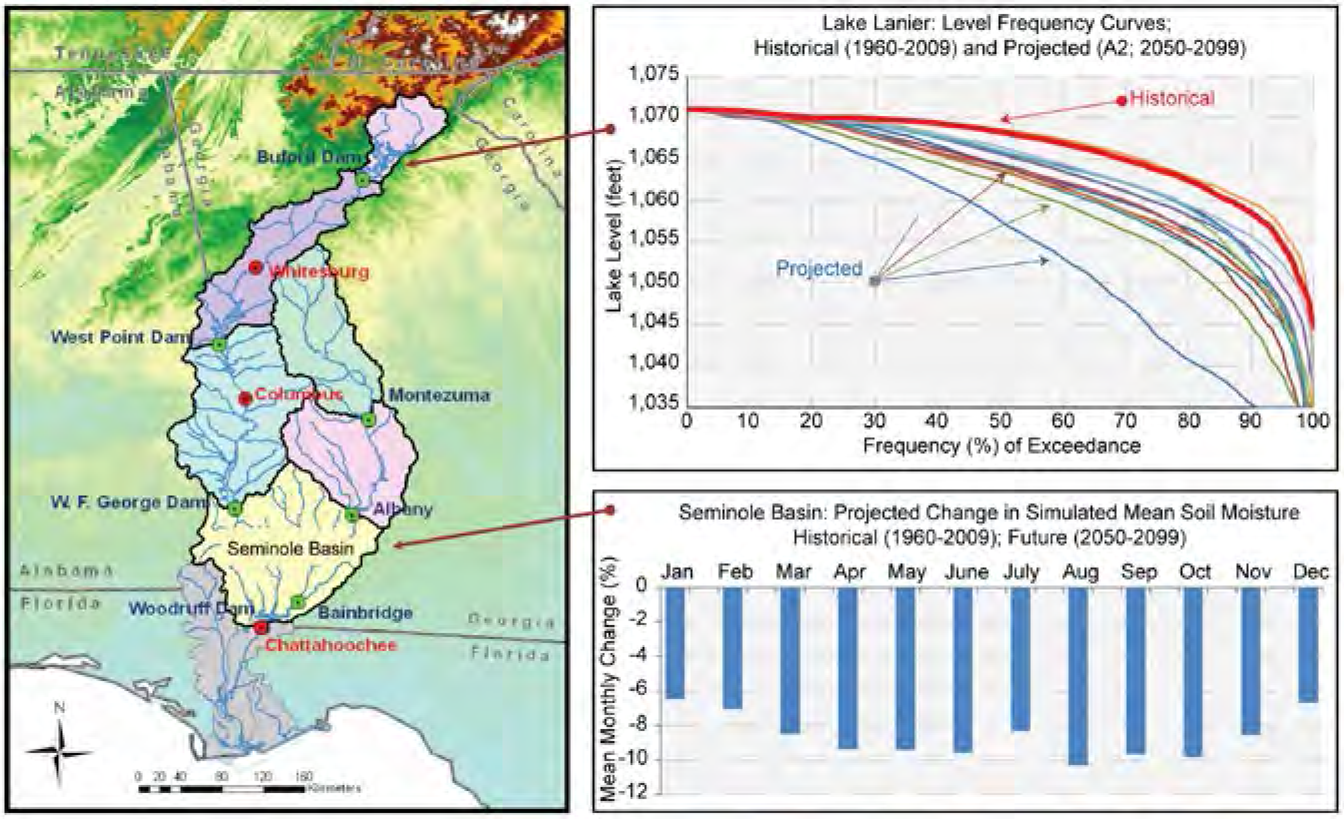


Figure 3.12. The Apalachicola-Chattahoochee-Flint (ACF) River Basin supports many water uses and users, including municipal, industrial, and agricultural water supply; flood management; hydroelectric and thermoelectric energy generation; recreation; navigation; fisheries; and a rich diversity of environmental and ecological resources. In recent decades, water demands have risen rapidly in the Upper Chattahoochee River (due to urban growth) and Lower Chattahoochee and Flint Rivers (due to expansion of irrigated agriculture). At the same time, basin precipitation, soil moisture, and runoff are declining, creating challenging water sharing tradeoffs for the basin stakeholders.[159] The historical water demand and supply trends are expected to continue in the coming decades. Climate assessments for 50 historical (1960-2009) and future years (2050-2099) based on a scenario of continued increases in emissions (A2) for the Seminole and all other ACF sub-basins[152] show that soil moisture is projected to continue to decline in all months, especially during the crop growing season from April to October (bottom right). Mean monthly runoff decreases (up to 20%, not shown) are also projected throughout the year and especially during the wet season from November to May. The projected soil moisture and runoff shifts are even more significant in the extreme values of the respective distributions. In addition to reduced supplies, these projections imply higher water demands in the agricultural and other sectors, exacerbating management challenges. These challenges are reflected in the projected response of Lake Lanier, the main ACF regulation project, the levels of which are projected (for 2050-2099) to be lower, by as much as 15 feet, than its historical (1960-2009) levels, particularly during droughts (top right). Recognizing these critical management challenges, the ACF stakeholders are earnestly working to develop a sustainable and equitable management plan that balances economic, ecological, and social values.[160] (Figure source: Georgia Water Resources Institute, Georgia Institute of Technology.[152]).

Key Message 11: Adaptation Opportunities and Challenges

Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.

Climate adaptation involves both addressing the risks and leveraging the opportunities that may arise as a result of the climate impacts on the water cycle and water resources. Efforts to increase resiliency and enhance adaptive capacity may create opportunities for a wide-ranging public discussion of water demands, improved collaboration around water use, increased public support for scientific and economic information, and the deployment of new technologies supporting adaptation. In addition, adaptation can promote the achievement of multiple water resource objectives through improved infrastructure planning, integrated regulation, and planning and management approaches at regional, watershed, or ecosystem scales. Pursuing these opportunities may require assessing how current institutional approaches support adaptation in light of the anticipated impacts of climate change.[161]

Climate change will stress the nation's aging water infrastructure to varying degrees by location and over time. Much of the country's current drainage infrastructure is already overwhelmed during heavy precipitation and high runoff events, an impact that is projected to be exacerbated as a result of climate change, land-use change, and other factors. Large percentage increases in combined sewage overflow volumes, associated with increased intensity of precipitation events, have been projected for selected watersheds by the end of this century in the absence of adaptive measures.[106,162] Infrastructure planning, especially for the long planning and operation horizons often associated with water resources infrastructure, can be improved by incorporating climate change as a factor in new design standards and in asset management and rehabilitation of critical and aging facilities, emphasizing flexibility, redundancy, and resiliency.[106,132,163]

Adaptation strategies for water infrastructure include structural and non-structural approaches. These may include changes in system operations and/or demand management changes, adopting water conserving plumbing codes, and improving flood forecasts, telecommunications, and early warning systems[164] that focus on both adapting physical structures and innovative management.[106,132,165] Such strategies could take advantage of conventional ("gray") infrastructure upgrades (like raising flood control levees); adjustments to reservoir operating rules; new demand management and incentive strategies; land-use management that enhances adaptive capacity; protection and restoration at the scale of river basins, watersheds, and ecosystems; hybrid strategies that blend "green" infrastructure with gray infrastructure; and pricing strategies.[1,106,132,166,167] Green infrastructure approaches that are increasingly being implemented by municipalities across the country include green roofs, rain gardens, roadside plantings, porous pavement, and rainwater harvesting (Ch. 28: Adaptation). These techniques typically utilize soils and vegetation in the built environment to absorb runoff close to where it falls, limiting flooding and sewer backups.[168] There are numerous non-infrastructure related adaptation strategies, some of which could include promoting drought-resistant crops, flood insurance reform, and building densely developed areas away from highly vulnerable areas.

In addition to physical adaptation, capacity-building activities can build knowledge and enhance communication and collaboration within and across sectors.[1,167,169] In particular, building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Ch. 26: Decision Support; Ch. 28: Adaptation).[170]

In addition to stressing the physical infrastructure of water systems, future impacts of climate change may reveal the weaknesses in existing water law regimes to accommodate novel and dynamic water management conditions. The basic paradigms of environmental and natural resources law are preservation and restoration, both of which are based on the assumption that natural systems fluctuate within an unchanging envelope of variability ("stationarity").[171] However, climate change is now projected to affect water supplies during the multi-decade lifetime of major water infrastructure projects in wide-ranging and pervasive ways.[132] Under these circumstances, stationarity will no longer be reliable as the central assumption in water-resource risk assessment and planning.[42,171] For example, in the future, water rights administrators may find it necessary to develop more flexible water rights systems conditioned to address the uncertain impacts of climate change.[172] Agencies and courts may seek added flexibility in regulations and laws to achieve the highest and best uses of limited water resources and to enhance water management capacity in the context of new and dynamic conditions.[132,173]

In the past few years, many federal, state, and local agencies and tribal governments have begun to address climate change adaptation, integrating it into existing decision-making, planning, or infrastructure-improvement processes (Ch. 28: Adaptation).[43,174] Drinking water utilities are increasingly utilizing climate information to prepare assessments of their supplies,[175] and utility associations and alliances, such as the Water Research Foundation and Water Utility Climate Alliance, have undertaken original research to better understand the implications of climate change on behalf of some of the largest municipal water utilities in the United States.[119,156,176]

The economic, social, and environmental implications of climate change induced water cycle changes are very significant, as is the cost of inaction. Adaptation responses need to address considerable uncertainties in the short-, medium-, and long-term; be proactive, integrated, and iterative; and be developed through well-informed stakeholder decision processes functioning within a flexible institutional and legal environment.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:

The chapter author team engaged in multiple technical discussions via teleconferences from March – June 2012. These discussions followed a thorough review of the literature, which included an inter-agency prepared foundational document,[1] over 500 technical inputs provided by the public, as well as other published literature. The author team met in Seattle, Washington, in May 2012 for expert deliberation of draft key messages by the authors wherein each message was defended before the entire author team before this key message was selected for inclusion in the Chapter. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities." Key messages were further refined following input from the NCADAC report integration team and authors of Ch. 2: Our Changing Climate.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 20: Southwest, other technical input reports,[2] and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe precipitation trends (Ch. 2: Our Changing Climate)[4,7,8,34] and river-flow trends.[13,41] As discussed in Chapter 2, the majority of projections available from climate models (for example, Orlowsky and Seneviratne 2012;[3] Kharin et al. 2013[5]) indicate small projected changes in total average annual precipitation in many areas, while heavy precipitation[6] and the length of dry spells are projected to increase across the entire country. Projected precipitation responses (such as changing extremes) to increasing greenhouse gases are robust in a wide variety of models and depictions of climate.

The broad observed trends of precipitation and river-flow increases have been identified by many long-term National Weather Service (NWS)/National Climatic Data Center (NCDC) weather monitoring networks, USGS streamflow monitoring networks, and analyses of records therefrom (Ch. 2: Our Changing Climate;[34,36,37]). Ensembles of climate models[3,42](see also Ch. 2: Our Changing Climate, Ch. 20: Southwest) are the basis for the reported projections.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Observed trends: Precipitation trends are generally embedded amidst large year-to-year natural variations and thus trends may be difficult to detect, may differ from site to site, and may be reflections of multi-decadal variations rather than external (human) forcings. Consequently, careful analyses of longest-term records from many stations across the country and addressing multiple potential explanations are required and are cornerstones of the evidentiary studies described above.

Efforts are underway to continually improve the stability, placement, and numbers of weather observations needed to document trends; scientists also regularly search for other previously unanalyzed data sources for use in testing these findings.

Projected trends: The complexity of physical processes that result in precipitation and runoff reduces abilities to represent or predict them as accurately as would be desired and with the spatial and temporal resolution required for many applications; however, as noted, the trends at the scale depicted in this message are very robust among a wide variety of climate models and projections, which lends confidence that the projections are appropriate lessons from current climate (and streamflow) models. Nonetheless, other influences not included in the climate change projections might influence future patterns of precipitation and runoff, including changes in land cover, water use (by humans and vegetation), and streamflow management.

Climate models used to make projections of future trends are continually increasing in number, resolution, and in the number of additional external and internal influences that might be confounding current projections. For example, much more of all three of these directions for improvement are already evident in projection archives for the next IPCC assessment.

Assessment of confidence based on evidence

Observed trends have been demonstrated by a broad range of methods over the past 20+ years based on best available data; projected precipitation and river-flow responses to greenhouse gas increases are robust across large majorities of available climate (and hydrologic) models from scientific teams around the world.

Confidence is therefore judged to be **high** that annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions.

Confidence is **high** that very heavy precipitation events have increased nationally and are projected to increase in all regions.

Confidence is **high** that the length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 16: Northeast, Ch 17: Southeast, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 21: Northwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Projected drought trends derive directly from climate models in some studies (for example, Hoerling et al. 2012;[8] Wehner et al. 2011;[30] Gao et al. 2012;[32] Gao et al. 2011;[33]), from hydrologic models responding to projected climate trends in others (for example, Georgakakos and Zhang 2011;[38] Cayan et al. 2010;[48]), from considerations of the interactions between precipitation deficits and either warmer or cooler temperatures in historical (observed) droughts,[48] and from combinations of these approaches (for example, Trenberth et al. 2004[49]) in still other studies.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Warmer temperatures are robustly projected by essentially all climate models, with what are generally expected to be directly attendant increases in the potentials for greater evapotranspiration, or ET (although it is possible that current estimates of future ET are overly influenced by temperatures at the expense of other climate variables, like wind speed, humidity, net surface radiation, and soil moisture that might change in ways that could partly ameliorate rising ET demands). As a consequence, there is a widespread expectation that more water from precipitation will be evaporated or transpired in the warmer future, so that except in regions where precipitation increases more than ET increases, less overall water will remain on the landscape and droughts will intensify and become more common. Another widespread expectation is that precipitation variability will increase, which may result in larger swings in moisture availability, with swings towards the deficit side resulting in increased frequencies and intensities of drought conditions on seasonal time scales to times scales of multiple decades. An important remaining uncertainty, discussed in the supporting text for Key Message #1, is the extent to which the types of models used to project future droughts may be influencing results with a notable recent tendency for studies with more complete, more resolved land-surface models, as well as climate models, to yield more moderate projected changes.

Other uncertainties derive from the possibility that changes in other variables or influences of CO_2-fertilization and/or land cover change may also partly ameliorate drought intensification. Furthermore in many parts of the country, El Niño-Southern Oscillation (and other oceanic) influences on droughts and floods are large, and can overwhelm climate change effects during the next few decades. At present, however, the future of these oceanic climate influences remains uncertain.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

Confidence is judged to be **medium-high** that short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Confidence is **high** that longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 16: Northeast, Ch 17: Southeast, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 21: Northwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

The principal observational bases for the key message are careful national-scale flood-trend analyses[58] based on annual peak-flow records from a selection of 200 USGS streamflow gaging stations measuring flows from catchments that are minimally influenced by upstream water uses, diversions, impoundments, or land-use changes with more than 85 years of records, and analyses of two other subsets of USGS gages with long records (including gages both impacted by human activities and less so), including one analysis of 50 gages nationwide[56] and a second analysis of 572 gages in the eastern United States.[57] There is some correspondence among regions with significant changes in annual precipitation (Ch. 2: Our Changing Climate) and soil moisture (Figures 3.2 and 3.3), and annual flood magnitudes (Figure 3.5).[58]

Projections of future flood-frequency changes result from detailed hydrologic models (for example, Das et al. 2012;[60] Raff et al. 2009;[133]Walker et al. 2011[135]) of rivers that simulate responses to projected precipitation and temperature changes from climate models; such simulations have only recently begun to emerge in the peer-reviewed literature.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Large uncertainties remain in efforts to detect flood-statistic changes attributable to climate change, because a wide range of local factors (such as dams, land-use changes, river channelization) also affect flood regimes and can mask, or proxy for, climate change induced alterations. Furthermore, it is especially difficult to detect any kinds of trends in what are, by definition, rare and extreme events. Finally, the response of floods to climate changes are expected to be fairly idiosyncratic from basin to basin, because of the strong influences of within-storm variations and local, basin-scale topographic, soil and vegetation, and river network characteristics that influence the size and extent of flooding associated with any given storm or season.[54,55,56,57]

Large uncertainties still exist as to how well climate models can represent and project future extremes of precipitation. This has – until recently – limited attempts to make specific projections of future flood frequencies by using climate model outputs directly or as direct inputs to hydrologic models. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall this results in increased flood potential; furthermore, occasional rain-on-snow events exacerbates this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.[62] Rising sea levels and projected increase in hurricane-associated storm intensity and rainfall rates provide first-principles bases for expecting intensified flood regimes in coastal settings (see Ch. 2: Our Changing Climate).

Assessment of confidence based on evidence

Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences, and the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, and upstream management). Consequently, flood frequency changes may be neither simple nor regionally homogeneous, and basin by basin projections may need to be developed. Early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and increasingly rainy (rather than snowy) storms in previously snow-dominated settings. Confidence in current estimates of future changes in flood frequencies and intensities is overall judged to be **low**.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] regional chapters of the NCA, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Several recent studies[65,66,67,68,71,72] have evaluated the potential impacts of changes in groundwater use and recharge under scenarios including climate change, and generally they have illustrated the common-sense conclusion that changes in pumpage can have immediate and significant effects in the nation's aquifers. This has certainly been the historical experience in most aquifers that have seen significant development; pumpage variations usually tend to yield more immediate and often larger changes on many aquifers than do historical climate variations on time scales from years to decades. Meanwhile, for aquifers in the Southwest, there is a growing literature of geochemical studies that fingerprint various properties of groundwater and that are demonstrating that most western groundwater derives preferentially from snowmelt, rather than rainfall or other sources.[50,51,66,74] This finding suggests that much western recharge may be at risk of changes and disruptions from projected losses of snowpack, but as yet provides relatively little indication whether the net effects will be recharge declines, increases, or simply spatial redistribution.

New information and remaining uncertainties

The precise responses of groundwater storage and flow to climate change are not well understood, but recent and ongoing studies provide insights on underlying mechanisms.[65,66,67] The observations and modeling evidence to make projections of future responses of groundwater recharge and discharge to climate change are thus far very limited, primarily because of limitations in data availability and in the models themselves. New forms and networks of observations and new modeling approaches and tools are needed to provide projections of the likely influences of climate changes on groundwater recharge and discharge. Despite the uncertainties about the specifics of climate change impacts on groundwater, impacts of reduced groundwater supply and quality would likely be detrimental to the nation.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is judged to be **high** that climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

Description of evidence base

This message has a strong theoretical and observational basis, including considerable historical experience with seawater intrusion into many of the nation's coastal aquifers and wetlands under the influence of heavy pumpage, some experience with the influences of droughts and storms on seawater intrusion, and experience with seepage of seawater into shallow coastal aquifers under storm and storm surge conditions that lead to coastal inundations with seawater. The likely influences of sea level rise on seawater intrusion into coastal (and island) aquifers and wetlands are somewhat less certain, as discussed below, although it is projected that sea level rise may increase opportunities for saltwater intrusion (see Ch. 25: Coasts).

New information and remaining uncertainties

There are few published studies describing the kinds of groundwater quality and flow modeling that are necessary to assess the real-world potentials for sea level rise to affect seawater intrusion.[78] Studies in the literature and historical experience demonstrate the detrimental impacts of alterations to the water budgets of the freshwater lenses in coastal aquifers and wetlands around the world (most often by groundwater development), but few evaluate the impacts of sea level rise alone. More studies with real-world aquifer geometries and development regimes are needed to reduce the current uncertainty of the potential interactions of sea level rise and seawater intrusion.

Assessment of confidence based on evidence

Confidence is **high** that sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

KEY MESSAGE #6 TRACEABLE ACCOUNT

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 8: Ecosystems, Ch. 15: Biogeochemical Cycles, and over 500 technical inputs on a wide range of topics that were reviewed as part of the Federal Register Notice solicitation for public input.

Thermal stratification of deep lakes and reservoirs has been observed to increase with increased air and water temperatures,[1,81,82] and may be eliminated in shallow lakes. Increased stratification reduces mixing, resulting in reduced oxygen in bottom waters. Deeper set-up of vertical thermal stratification in lakes and reservoirs may reduce or eliminate a bottom cold water zone; this, coupled with lower oxygen concentration, results in a degraded aquatic ecosystem.

Major precipitation events and resultant water flows increase watershed pollutant scour and thus increase pollutant loads.[84] Fluxes of mineral weathering products (for example, calcium, magnesium, sodium, and silicon) have also been shown to increase in response to higher discharge.[86] In the Mississippi drainage basin, increased precipitation has resulted in increased nitrogen loads contributing to hypoxia in the Gulf of Mexico.[85] Models predict and observations confirm that continued warming will have increasingly negative effects on lake water quality and ecosystem health.[81]

Future re-mobilization of sediment stored in large river basins will be influenced by changes in flood frequencies and magnitudes, as well as on vegetation changes in the context of climate and other anthropogenic factors.[87] Model projections suggest that changes in sediment delivery will vary regionally and by land-use type, but on average could increase by 25% to 55%.[88]

New information and remaining uncertainties

It is unclear whether increasing floods and droughts cancel each other out with respect to long-term pollutant loads.

It is also uncertain whether the absolute temperature differential with depth will remain constant, even with overall lake and reservoir water temperature increases. Further, it is uncertain if greater mixing with depth will eliminate thermal stratification in shallow, previously stratified lakes. Although recent studies of Lake Tahoe provide an example of longer stratification seasons,[83] lakes in other settings and with other geometries may not exhibit the same response.

Many factors influence stream water temperature, including air temperature, forest canopy cover, and ratio of baseflow to streamflow.

Assessment of confidence based on evidence

Given the evidence base, confidence is **medium** that increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and pollutant loads.

KEY MESSAGE #7 TRACEABLE ACCOUNT

Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 17: Southeast, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawai‘i and Pacific Islands, and many technical inputs on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Observed Trends: Historical water withdrawals by sector (for example, municipal, industrial, agricultural, and thermoelectric) have been monitored and documented by USGS for over 40 years and represent a credible database to assess water-use trends, efficiencies, and underlying drivers. Water-use drivers principally include population, personal income, electricity consumption, irrigated area, mean annual temperature, growing season precipitation, and growing season potential evapotranspiration.[99] Water-use efficiencies are also affected by many non-climate factors, including demand management, plumbing codes, water efficient appliances, efficiency improvement programs, and pricing strategies;[100] changes from water intensive manufacturing and other heavy industrial activities to service-oriented businesses,[101] and enhanced water-use efficiencies in response to environmental pollution legislation; replacement of older once-through-cooling electric power plants by plants that recycle their cooling water; and switching from flood irrigation to more efficient methods in the western United States.[102]

Projected Trends and Consequences: Future projections have been carried out with and without climate change to first assess the water demand impacts of projected population and socioeconomic increases, and subsequently combine them with climate change induced impacts. The main findings are that in the absence of climate change total water withdrawals in the U.S. will increase by 3% in the coming 50 years,[99] with approximately half of the U.S. experiencing a total water demand decrease and half an increase. If, however, climate change projections are also factored in, the demand for total water withdrawals is projected to rise by an average of 26%,[99] with more than 90% of the U.S. projected to experience a total demand increase, and decreases projected only in parts of the Midwest, Northeast, and Southeast. When coupled with the observed and projected drying water cycle trends (see key messages in "Climate Change Impacts on the Water Cycle" section), the water demand impacts of projected population, socioeconomic, and climate changes intensify and compound in the Southwest and Southeast, rendering these regions particularly vulnerable in the coming decades.

New information and remaining uncertainties

The studies of water demand in response to climate change and other stressors are very recent and constitute new information on their own merit.[99] In addition, for the first time, these studies make it possible to piece together the regional implications of climate change induced water cycle alterations in combination with projected changes in water demand. Such integrated assessments also constitute new information and knowledge building.

Demand projections include various uncertain assumptions which become increasingly important in longer term (multi-decadal) projections. Because irrigation demand is the largest water demand component most sensitive to climate change, the most important climate-related uncertainties are precipitation and potential evapotranspiration over the growing season. Non-climatic uncertainties relate to future population distribution, socioeconomic changes, and water-use efficiency improvements.

Assessment of confidence based on evidence

Considering that (a) droughts are projected to intensify in large areas of the Southwest, Great Plains, and the Southeast, and (b) that these same regions have experienced and are projected to experience continuing population and demand increases, confidence that these regions will become increasingly vulnerable to climate change is judged to be **high**.

KEY MESSAGE #8 TRACEABLE ACCOUNT

Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 17: Southeast, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Observed Trends: Observations suggest that the water cycle in the Southwest, Great Plains, and Southeast has been changing toward drier conditions (Ch. 17: Southeast).[130,151,152] Furthermore, paleoclimate tree-ring reconstructions indicate that drought in previous centuries has been more intense and of longer duration than the most extreme drought of the 20th and 21st centuries.[40]

Projected Trends and Consequences: Global Climate Model (GCM) projections indicate that this trend is likely to persist, with runoff reductions (in the range of 10% to 20% over the next 50 years) and intensifying droughts.[48]

The drying water cycle is expected to affect all human and ecological water uses, especially in the Southwest. Decreasing precipitation, rising temperatures, and drying soils are projected to increase irrigation and outdoor watering demand (which account for nearly 90% of consumptive water use) by as much as 34% by 2060 under the A2 emissions scenario.[99] Decreasing runoff and groundwater recharge are expected to reduce surface and groundwater supplies,[66] increasing the annual risk of water shortages from 25% to 50% by 2060.[130] Changes in streamflow timing will increase the mismatch of supply and demand. Earlier and declining streamflow and rising demands will make it more difficult to manage reservoirs, aquifers, and other water infrastructure.[130]

Such impacts and consequences have been identified for several southwestern and western river basins including the Colorado,[38] Rio Grande,[126] and Sacramento-San Joaquin.[127,128,129]

New information and remaining uncertainties

The drying climate trend observed in the Southwest and Southeast in the last decades is consistent across all water cycle variables (precipitation, temperature, snow cover, runoff, streamflow, reservoir levels, and soil moisture) and is not debatable. The debate is over whether this trend is part of a multi-decadal climate cycle and whether it will reverse direction at some future time. However, the rate of change and the comparative GCM assessment results with and without historical CO_2 forcing (Ch. 2: Our Changing Climate) support the view that the observed trends are due to both factors acting concurrently.

GCMs continue to be uncertain with respect to precipitation, but they are very consistent with respect to temperature. Runoff, streamflow, and soil moisture depend on both variables and are thus less susceptible to GCM precipitation uncertainty. The observed trends and the general GCM agreement that the southern states will continue to experience streamflow and soil moisture reductions[34,41] provides confidence that these projections are robust.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high** that changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. Confidence is **high** that these trends are expected to continue, increasing the likelihood of water shortages for many uses.

KEY MESSAGE #9 TRACEABLE ACCOUNT

Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 21: Northwest, Ch. 19: Great Plains, Ch. 18: Midwest, Ch. 16: Northeast, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Observed Trends: Very heavy precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Increasing heavy precipitation is an important contributing factor for floods, but flood magnitude changes also depend on specific watershed conditions (including soil moisture, impervious area, and other human-caused alterations). There is, however, some correspondence among regions with significant changes in annual precipitation (Ch. 2: Our Changing Climate), soil moisture (Figures 3.2 and 3.3), and annual flood magnitudes (Figure 3.5).[58]

Flooding and seawater intrusion from sea level rise and increasing storm surge threaten New York, Boston, Philadelphia, Virginia Beach, Wilmington, Charleston, Miami, Tampa, Naples, Mobile, Houston, New Orleans, and many other coastal cities (Chapter 25: Coasts).

Projected Trends: Projections of future flood-frequency changes result from detailed hydrologic[60,133,135] and hydraulic models of rivers that simulate responses to projected precipitation and temperature changes from climate models.

Consequences: Floods already affect human health and safety and result in substantial economic, ecological, and infrastructure damages. Many cities are located along coasts and, in some of these cities (including New York, Boston, Miami, Savannah, and New Orleans), sea level rise is expected to exacerbate coastal flooding issues by backing up flood flows and impeding flood-management responses (see Ch. 16: Northeast and Ch. 25: Coasts).[136]

Projected changes in flood frequency and severity can bring new challenges in flood risk management. For urban areas in particular, flooding impacts critical infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (for example, failure of electrical generating lines can cause pump failure, additional flooding, and failure of evacuation services). Increasing likelihood of flooding also brings with it human health risks associated with failure of critical infrastructure (Ch. 11: Urban),[137] from waterborne disease that can persist well beyond the occurrence of very heavy precipitation (Ch. 9: Human Health),[139] from water outages associated with infrastructure failures that cause decreased sanitary conditions,[138] and from ecosystem changes that can affect airborne diseases (Ch. 8: Ecosystems).[140]

New information and remaining uncertainties

Large uncertainties still exist as to how well climate models can represent and project future precipitation extremes. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall, this results in increased flood potential; furthermore occasional rain-on-snow events exacerbate this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.[62]

Assessment of confidence based on evidence

Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences and on the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, and upstream managements). Consequently, flood frequency changes may be neither simple nor regionally homogeneous, and basin by basin projections may need to be developed. Nonetheless, early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and more rainfall runoff from previously snowbound catchments and settings.

Therefore, confidence is judged to be **medium** that increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

KEY MESSAGE #10 TRACEABLE ACCOUNT

In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] other chapters of the NCA, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Observed and Projected Trends: Many U.S. regions are facing critical water management and planning challenges. Recent assessments illustrate water management challenges facing California,[127,128,129,149] the Southwest,[130,151] Southeast (Ch. 17: Southeast),[136,152] Northwest,[153] Great Plains,[154] and Great Lakes.[155]

The Sacramento-San Joaquin Bay Delta is already threatened by flooding, seawater intrusion, and changing needs for environmental, municipal, and agricultural water uses. Managing these risks and uses requires reassessment of a very complex system of water rights, levees, stakeholder consensus processes, reservoir system operations, and significant investments, all of which are subject to large uncertainties.[54,148] Given the projected climate changes in the Sacramento-San Joaquin Bay Delta, adherence to historical management and planning practices may not be a long-term viable option,[128,129] but the supporting science is not yet fully actionable,[42] and a flexible legal and policy framework embracing change and uncertainty is lacking.

The Apalachicola-Chattahoochee-Flint (ACF) River basin in Georgia, Alabama, and Florida supports a wide range of water uses and the regional economy, creating challenging water-sharing tradeoffs for the basin stakeholders. Climate change presents new stresses and uncertainties.[152] ACF stakeholders are working to develop a management plan that balances economic, ecological, and social values.[160]

New information and remaining uncertainties

Changes in climate, water demand, land use, and demography combine to challenge water management in unprecedented ways. This is happening with a very high degree of certainty in most U.S. regions. Regardless of its underlying causes, climate change poses difficult challenges for water management because it invalidates stationarity – the perception that climate varies around a predictable mean based on the experience of the last century – and increases hydrologic variability and uncertainty. These conditions suggest that past management practices will become increasingly ineffective and that water management can benefit by the adoption of iterative, risk-based, and adaptive approaches.

Assessment of confidence based on evidence

The water resources literature is unanimous that water management should rely less on historical practices and responses and more on robust, risk-based, and adaptive decision approaches.

Therefore confidence is **very high** that in most U.S. regions, water resources managers and planners will face new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.

KEY MESSAGE #11 TRACEABLE ACCOUNT

Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document[1] and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

There are many examples of adaptive strategies for water infrastructure[106,132,164,165] as well as strategies for demand management, land-use and watershed management, and use of "green" infrastructure.[1,106,132,166,167]

Building adaptive capacity ultimately increases the ability to develop and implement adaptation strategies and is considered a no-regrets strategy.[1,169] Building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Ch. 26: Decision Support; Ch. 28: Adaptation).[170]

Water utility associations have undertaken original research to better understand the implications of climate change on behalf of some of the largest municipal water utilities in the United States.[119,156,176]

Challenges include "stationarity" no longer being reliable as the central assumption in water-resource planning,[171] considerable uncertainties, insufficient actionable science ready for practical application, the challenges of stakeholder engagement, and a lack of agreement on "post-stationarity" paradigms on which to base water laws, regulations, and policies.[42] Water administrators may find it necessary to develop more flexible water rights and regulations.[132,172,173]

New information and remaining uncertainties

Jurisdictions at the state and local levels are addressing climate change related legal and institutional issues on an individual basis. An ongoing assessment of these efforts may show more practical applications.

Assessment of confidence based on evidence

Confidence is **very high** that increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts.

Confidence is **very high** that many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.

Climate Change Impacts in the United States

CHAPTER 4
ENERGY SUPPLY AND USE

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4 ENERGY SUPPLY AND USE

KEY MESSAGES

1. **Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of certain types of extreme weather events are expected to change.**
2. **Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase.**
3. **Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production.**
4. **In the longer term, sea level rise, extreme storm surge events, and high tides will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.**
5. **As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways. Depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.**

The U.S. energy supply system is diverse and robust in its ability to provide a secure supply of energy with only occasional interruptions. However, projected impacts of climate change will increase energy use in the summer and pose additional risks to reliable energy supply. Extreme weather events and water shortages are already interrupting energy supply, and impacts are expected to increase in the future. Most vulnerabilities and risks to energy supply and use are unique to local situations; others are national in scope.

In addition to being vulnerable to the effects of climate change, electricity generation is a major source of the heat-trapping gases that contribute to climate change. Therefore, regulatory or policy efforts aimed at reducing emissions would also affect the energy supply system. See Ch. 10: Energy, Water, and Land, Key Message 2; and Ch. 27: Mitigation for more on this topic. This chapter focuses on impacts of climate change to the energy sector.

Energy infrastructure around the country has been compromised by extreme weather events.

The impacts of climate change in other countries will also affect U.S. energy systems through global and regional cross-border markets and policies. Increased energy demand within global markets due to industrialization, population growth, and other factors will influence U.S. energy costs through competition for imported and exported energy products. The physical impacts of climate change on future energy systems in the 25- to 100-year timeframe will depend on how those energy systems evolve. That evolution will be driven by multiple factors, including technology innovations and carbon emission constraints.

Adaptation actions can allow energy infrastructure to adjust more readily to climate change. Many investments toward adaptation provide short-term benefits because they address current vulnerabilities as well as future risks, and thus entail "no regrets." Such actions can include a focus on increased efficiency of energy use as well as improvements in the reliability of production and transmission of energy. The general concept of adaptation is presented in Chapter 28: Adaptation.

Key Message 1: Disruptions from Extreme Weather

Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of certain types of extreme weather events are expected to change.

Much of America's energy infrastructure is vulnerable to extreme weather events. Because so many components of U.S. energy supplies – like coal, oil, and electricity – move from one area to another, extreme weather events affecting energy infrastructure in one place can lead to supply consequences elsewhere.

Climate change has begun to affect the frequency, intensity, and length of certain types of extreme weather events.[1,2,3] What is considered an extreme weather or climate event varies from place to place. Observed changes across most of the U.S. include increased frequency and intensity of extreme precipitation events, sustained summer heat, and in some regions, droughts and winter storms. The frequency of cold waves has decreased (Ch. 2: Our Changing Climate).

Projected climate changes include increases in various types of extreme weather events, particularly heat waves, wildfire, longer and more intense drought, more frequent and intense very heavy precipitation events, and extreme coastal high water due to heavy-precipitation storm events coupled with sea level rise. Extreme coastal high water will increasingly disrupt infrastructure services in some locations.[4] The frequency of cold waves is expected to continue decreasing. Disruptions in services in one infrastructure system (such as energy) will lead to disruptions in one or more other infrastructures (such as communications and transportation) that depend on other affected systems. Infrastructure exposed to extreme weather and also stressed by age or by demand that exceeds designed levels is particularly vulnerable (see Ch. 11: Urban).

Like much of the nation's infrastructure affected by major weather events with estimated economic damages greater than $1 billion,[5,6] U.S. energy facilities and systems, especially those located in coastal areas, are vulnerable to extreme weather events. Wind and storm surge damage by hurricanes already causes significant infrastructure losses on the Gulf Coast.

In 2005, damage to oil and gas production and delivery infrastructure by Hurricanes Katrina and Rita affected natural gas, oil, and electricity markets in most parts of the United States.[4,7] Market impacts were felt as far away as New York and New England,[8,9] highlighting the significant indirect economic impacts of climate-related events that go well beyond the direct damages to energy infrastructure.

Various aspects of climate change will affect and disrupt energy distribution and energy production systems. It is projected that wildfires will affect extensive portions of California's electricity transmission grid.[10] Extreme storm surge events at high tides are expected to increase,[11] raising the risk of inundating energy facilities such as power plants, refineries, pipelines, and transmission and distribution networks. Rail transportation lines that carry coal to power plants, which produced 42% of U.S. electricity in 2011, often follow riverbeds. More intense rainstorms can lead to river flooding that degrades or washes out nearby railroads and roadbeds, and increases in rainstorm intensity have been observed and are projected to continue.

Paths of Hurricanes Katrina and Rita Relative to Oil and Gas Production Facilities

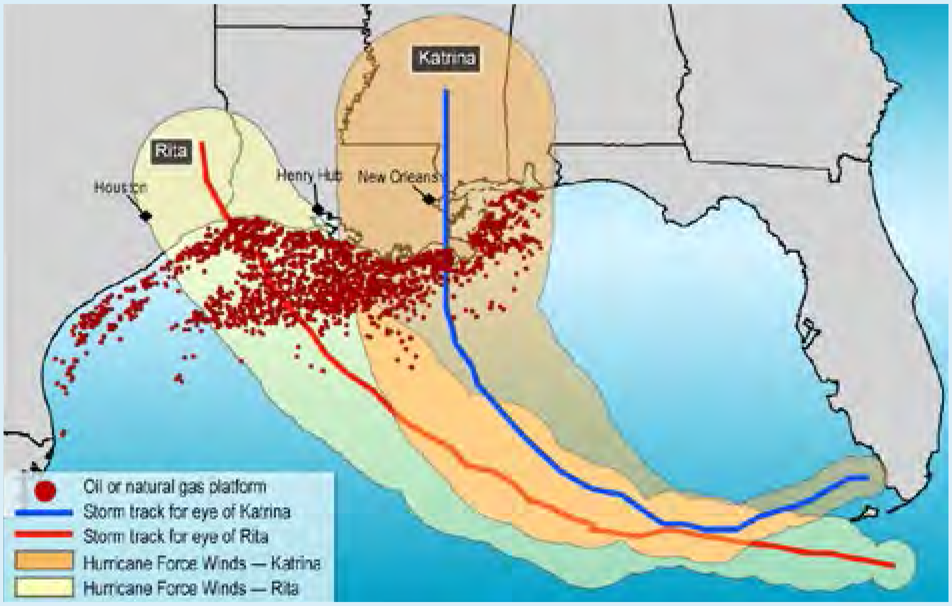


Figure 4.1. A substantial portion of U.S. energy facilities is located on the Gulf Coast as well as offshore in the Gulf of Mexico, where they are particularly vulnerable to hurricanes and other storms and sea level rise. (Figure source: U.S. Government Accountability Office 2006).

By learning from previous events, offshore operations can be made more resilient to the impacts of hurricanes. During Hurricane Isaac in August 2012, the U.S. Bureau of Safety and Environmental Enforcement reported that oil and gas production was safely shut down and restarted within days of the event.[12]

The geographical diversification of energy sources away from hurricane-prone areas such as the Gulf of Mexico has reduced vulnerability to hurricanes. The U.S. Energy Information Administration (EIA) reports that the percentage of natural gas production from the Gulf of Mexico shifted from 20% in 2005 to 7% in 2012.[13] This is due to the development of shale gas production in other parts of the United States.

Key Message 2: Climate Change and Seasonal Energy Demands

Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase.

Over the last 20 years, annual average temperatures typically have been higher than the long-term average; nationally, temperatures were above average during 12 of the last 14 summers (Ch. 2: Our Changing Climate).[2] These increased temperatures are already affecting the demand for energy needed to cool buildings in the United States.

Average temperatures have increased in recent decades. In response, the Energy Information Administration began using 10-year average weather data instead of 30-year average weather data in order to estimate energy demands for heating and cooling purposes. The shorter period is more consistent with the observed trend of warmer winters and summers,[14] but is still not necessarily optimal for anticipating near-term temperatures.[17]

While recognizing that many factors besides climate change affect energy demand (including population changes, economic conditions, energy prices, consumer behavior, conservation programs, and changes in energy-using equipment), increases in temperature will result in increased energy use for cooling and decreased energy use for heating. These impacts differ among regions of the country and indicate a shift from predominantly heating to predominantly cooling in some regions with moderate climates. For example, in the Northwest, energy demand for cooling is projected to increase over the next century due to population growth, increased cooling degree days, and increased use of air conditioners as people adapt to higher temperatures.[19] Population growth is also expected to increase energy demand for heating. However, the projected increase in energy demand for heating is about half as much when the effects of a warming climate are considered along with population growth.[19]

Demands for electricity for cooling are expected to increase in every U.S. region as a result of increases in average temperatures and high temperature extremes. The electrical grid handles virtually the entire cooling load, while the heating load is distributed among electricity, natural gas, heating oil, passive solar, and biofuel. In order to meet increased demands for peak electricity, additional generation and distribution facilities will be needed, or demand will have to be managed through a variety of mechanisms. Electricity at peak demand typically is more expensive to supply than at average demand.[21] Because the balance between heating and cooling differs by location, the balance of energy use among delivery forms and fuel types will likely shift from natural gas and fuel oil used for heating to electricity used for air conditioning. In hotter conditions, more fuel and energy are required to generate and deliver electricity, so increases in air conditioning use and shifts from heating to cooling in regions with moderate climates will increase primary energy demands.[4]

Increase in Cooling Demand and Decrease in Heating Demand

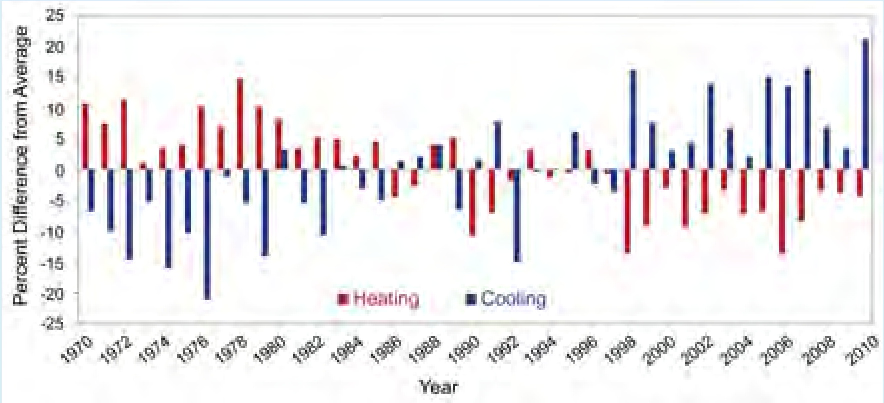


Figure 4.2. The amount of energy needed to cool (or warm) buildings is proportional to cooling (or heating) degree days. The figure shows increases in population-weighted cooling degree days, which result in increased air conditioning use, and decreases in population-weighted heating degree days, meaning less energy required to heat buildings in winter, compared to the average for 1970-2000. Cooling degree days are defined as the number of degrees that a day's average temperature is above 65ºF, while heating degree days are the number of degrees a day's average temperature is below 65ºF. As shown, the increase in cooling needs is greater than the decrease in heating needs (Data from NOAA NCDC 2012[16]).

Increase in Numbers of Cooling Degree Days

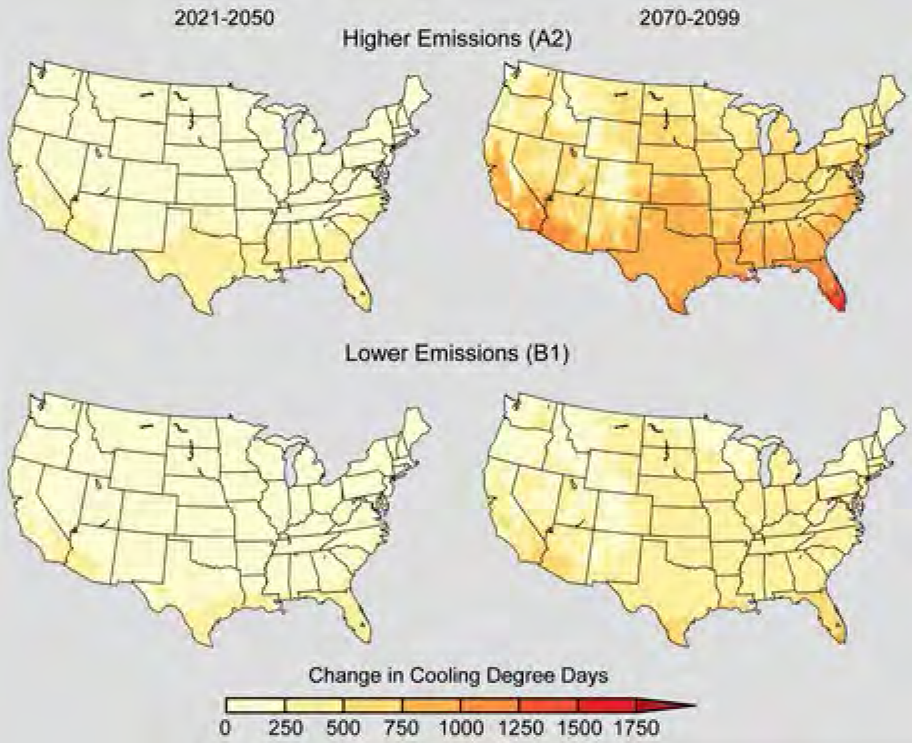


Figure 4.3. These maps show projected average changes in cooling degree days for two future time periods: 2021-2050 and 2070-2099 (as compared to the period 1971-2000). The top panel assumes climate change associated with continued increases in emissions of heat-trapping gases (A2), while the bottom panel assumes significant reductions (B1). The projections show significant regional variations, with the greatest increases in the southern United States by the end of this century under the higher emissions scenario. Furthermore, population projections suggest continued shifts toward areas that require air conditioning in the summer, thereby increasing the impact of temperature changes on increased energy demand.[18] (Figure source: NOAA NCDC / CICS-NC).

Table 4.1. Hotter and longer summers will increase the amount of electricity necessary to run air conditioning, especially in the Southeast and Southwest. Warmer winters will decrease the amount of natural gas required to heat buildings, especially in the Northeast, Midwest, and Northwest. Table information is adapted from multi-model means from 8 NARCCAP regional climate simulations for the higher emissions scenario (A2) considered in this report and is weighted by population. (Source: adapted from Regional Climate Trends and Scenarios reports[20])

Changing Energy Use for Heating and Cooling Will Vary by Region

	Consequences: Challenges and Opportunities	
Region	**Cooling**	**Heating**
Physical Impacts - High Likelihood	**Hotter and Longer Summers** Number of additional extreme hot days (> 95°F) and % increase in cooling degree days per year in 2041-2070 above 1971-2000 level	**Warmer Winters** Number of fewer extreme cold days (< 10°F) and % decrease in heating degree days per year in 2041-2070 below 1971-2000 level
Northeast	+10 days, +77%	-12 days, -17%
Southeast	+23 days, +43%	-2 days, -19%
Midwest	+14 days, +64%	-14 days, -15%
Great Plains	+22 days, +37%	-4 days, -18%
Southwest	+20 days, +44%	-3 days, -20%
Northwest	+5 days, +89%	-7 days, -15%
Alaska	Not studied	Not studied
Pacific Islands	Not studied	Not studied

Climate-related temperature shifts are expected to cause a net increase in residential electricity use.[21,22] Increased electricity demands for cooling will exceed electricity savings resulting from lower energy demands for heating. One study examining state-level energy consumption, weather data, and high emission scenarios (A2 and A1FI; Appendix 3: Climate Science Supplement) found a net increase of 11% in residential energy demand.[23] Another study reported annual increases in net energy expenditures for cooling and heating of about 10% ($26 billion in 1990 U.S. dollars) by the end of this century for 4.5°F of warming, and 22% ($57 billion in 1990 dollars) for overall warming of about 9°F.[24] New energy-efficient technology could help to offset growth in demand.

Several studies suggest that if substantial reductions in emissions of heat-trapping gases were required, the electricity generating sector would switch to using alternative (non-fossil) fuel sources first, given the multiple options available to generate electricity from sources that do not emit heat-trapping gases, such as wind and solar power. Under these circumstances, electricity would displace direct use of fossil fuels for some applications, such as heating, to reduce overall emissions of heat-trapping gases.[25,26] The implications for peak electricity demand could be significant. In California, for example, the estimated increase in use of electricity for space heating would shift the peak in electricity demand from summer to winter.[27] In addition, the fact that electricity from wind and solar is highly variable and may not be available when needed has the potential to decrease the reliability of the electricity system. However, some initial studies suggest that a well-designed electricity system with high penetration of renewable sources of energy should not decrease reliability (for example, Hand et al. 2012[28]).

Key Message 3: Implications of Less Water for Energy Production

Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production.

Producing energy from fossil fuels (coal, oil, and natural gas), nuclear power, biofuels, hydropower, and some solar power systems often requires adequate and sustainable supplies of water. Issues relatabled to water, including availability and restrictions on the temperature of cooling water returned to streams, already pose challenges to production from existing power plants and the ability to obtain permits to build new facilities (Ch. 10: Energy, Water, and Land).[21,29,30]

In the future, long-term precipitation changes, drought, and reduced snowpack are projected to alter water availability (Ch. 3: Water). Recent climate data indicate a national average increase in annual precipitation, owing to significant increases across the central and northeastern portions of the nation and a mix of increases and decreases elsewhere (Ch. 2: Our Changing Climate, Figure 2.12). Projected changes in precipitation are small in most areas of the United States, but vary both seasonally and regionally (Figure 4.4). The number of heavy downpours has generally increased and is projected to increase for all regions (Ch 2: Our Changing Climate, Figures 2.16, 2.17, 2.18, and 2.19).

Different analyses of observed changes in dry spell length do not show clear trends,[31] but longer dry spells are projected in southern regions and the Northwest (Ch. 2: Our Changing Climate, Figure 2.13) as a result of projected large-scale changes in circulation patterns.

Regional or seasonal water constraints, particularly in the Southwest and Southeast, will result from chronic or seasonal drought, growing populations, and increasing demand for water for various uses (Ch. 2: Our Changing Climate; Ch. 10: Energy, Water, and Land).[29,32] Reduced availability of water for cooling, for hydropower, or for absorbing warm water discharges into water bodies without exceeding temperature limits, will continue to constrain power production at existing facilities and permitting of new power plants. Increases in water temperatures may reduce the efficiency of thermal power plant cooling technologies, potentially leading to warmer water discharge from some power plants, which in turn can affect aquatic life. Studies conducted during 2012 indicate that there is an increasing likelihood of water shortages limiting power plant electricity production in many regions.[21,33]

Hydropower plants in the western United States depend on the seasonal cycle of snowmelt to provide steady output throughout the year. Expected reductions in snowpack in parts of the western U.S. will reduce hydropower production. There will also be increases in energy (primarily electricity) demand in order to pump water for irrigated agriculture and to pump and treat water for municipal uses.[21]

Projected Changes in Seasonal Precipitation

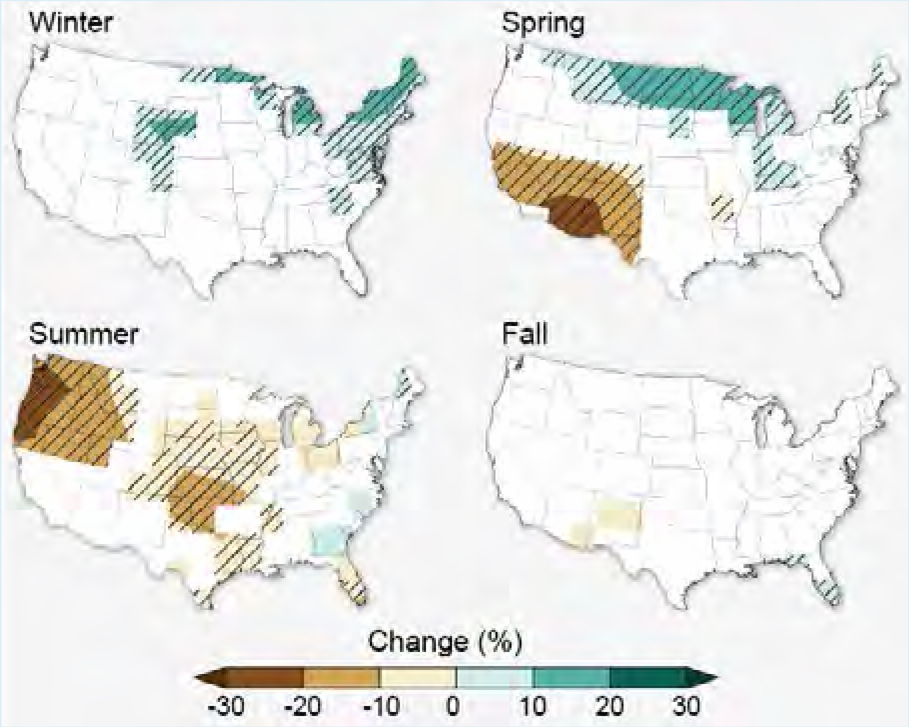


Figure 4.4. Climate change affects precipitation patterns as well as temperature patterns. The maps show projected changes in average precipitation by season for 2041–2070 compared to 1971–1999, assuming emissions of heat-trapping gases continue to rise (A2 scenario). Note significantly drier conditions in the Southwest in spring and Northwest in summer, as well as significantly more precipitation (some of which could fall as snow) projected for northern areas in winter and spring. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. (Figure source: NOAA NCDC / CICS-NC).

The Electric Power Research Institute's (EPRI) scenario-based technical projections of water demand in 2030 find that one-quarter of existing power generation facilities (about 240,000 megawatts) nationwide are in counties that face some type of water sustainability issue.[34] Many regions face water sustainability concerns, with the most significant water-related stresses in the Southeast, Southwest, and Great Plains regions (Ch. 3: Water).[34]

Key Message 4: Sea Level Rise and Infrastructure Damage

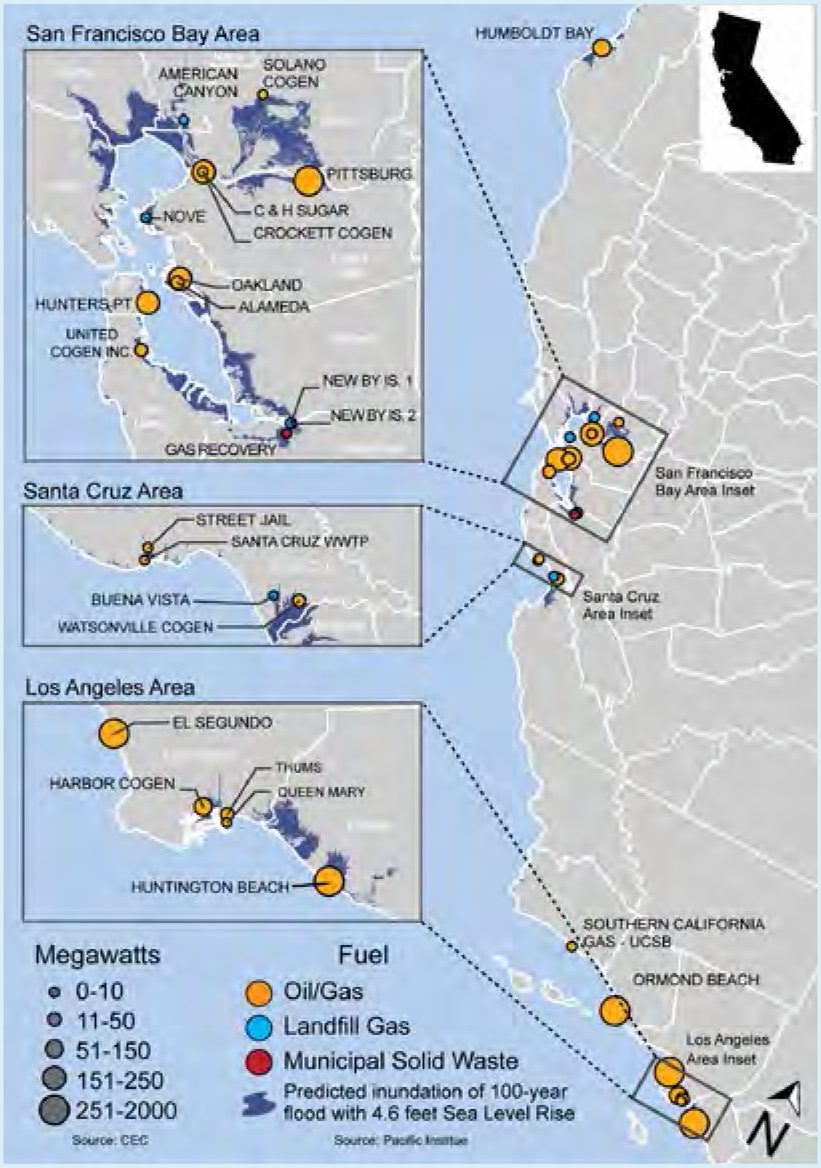
In the longer term, sea level rise, extreme storm surge events, and high tides will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

Significant portions of the nation's energy production and delivery infrastructure are in low-lying coastal areas; these facilities include oil and natural gas production and delivery facilities, refineries, power plants, and transmission lines.

Global sea level has risen by about 8 inches since reliable record keeping began in 1880, affecting countries throughout the world, including the United States. The rate of rise increased in recent decades and is not expected to slow. Global average sea level is projected to rise 1 to 4 feet by 2100 and is expected to continue to rise well beyond this century (Ch. 2: Our Changing Climate). Sea level change at any particular location can deviate substantially from this global average (Ch. 2: Our Changing Climate).[35]

Rising sea levels, combined with normal and potentially more intense coastal storms, an increase in very heavy precipitation events, and local land subsidence, threaten coastal energy equipment as a result of inundation, flooding, and erosion. This can be compounded in areas that are projected to receive more precipitation. In particular, sea level rise and coastal storms pose a danger to the dense network of Outer Continental Shelf marine and coastal facilities in the central Gulf Coast region.[36] Many of California's power plants are at risk from rising sea levels, which result in more extensive coastal storm flooding, especially in the low-lying San Francisco Bay area (Figure 4.5). Power plants and energy infrastructure in coastal areas throughout the United States face similar risks.

California Power Plants Potentially at Risk from Sea Level Rise



Source: CEC

Source: Pacific Institute

Figure 4.5. Rising sea levels will combine with storm surges and high tides to threaten power-generating facilities located in California coastal communities and around the San Francisco Bay. Sea level rise and more intense heavy precipitation events increase the risk of coastal flooding and damages to infrastructure (Ch. 3: Water). (Figure source: Sathaye et al. 2011[37]).

Key Message 5: Future Energy Systems

As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways. Depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.

Countless aspects of the U.S. economy today are supported by reliable, affordable, and accessible energy supplies. Electricity and other forms of energy are necessary for telecommunications, water and sewer systems, banking, public safety, and more. Today's energy systems vary significantly by region, however, with differences in climate-related impacts also introducing considerable variation by locale. Table 4.3 shows projected impacts of climate change on, and potential risks to, energy systems as they currently exist in different regions. Most vulnerabilities and risks for energy supply and use are unique to local situations, but others are national in scope. For example, biofuels production in three regions (Midwest, Great Plains, and Southwest) could be affected by the projected decrease in precipitation during the critical growing season in the summer months (Ch. 10: Energy, Water, and Land; Ch. 7: Forests).

One certainty about future energy systems is that they will be different than today's, but in ways not yet known. Many uncertainties – financial, economic, regulatory, technological, and so on – will affect private and public consumption and investment decisions on energy fuels, infrastructure, and systems. Energy systems will evolve over time, depending upon myriad choices made by countless decision-makers responding to changing conditions in markets, technologies, policies, consumer preferences, and climate. A key challenge to understanding the nature and intensity of climate change impacts on future energy systems is the amount of uncertainty regarding future choices about energy technologies and their deployment. An evolving energy system is also an opportunity to develop an energy system that is more resilient and less vulnerable to climate change.

Very different future energy supply portfolios are possible depending upon key economic assumptions, including what climate legislation may look like,[14,25,34] and whether significant changes in consumption patterns occur for a variety of other reasons. Renewable energy sources, including solar, wind, hydropower, biofuels, and geothermal are meeting a growing portion of U.S. demand, and there is the opportunity for this contribution to increase in the future (Ch. 6: Agriculture; Ch. 7: Forests). This fundamental uncertainty about the evolving character of energy systems contributes another layer of complexity to understanding how climate change will affect energy systems.

As they consider actions to enhance the resiliency of energy systems, decision-makers confront issues with current energy systems as well as possible future configurations. The systems will evolve and will be more resilient over time if actions tied to features of today's systems do not make future systems less resilient as a result. For example, if moving toward biomass as an energy source involves more water-consumptive energy supplies that could be constrained by drier future climate conditions, then decisions about energy choices should be made with consideration of potential changes in climate conditions and the risks these changes present (See Ch. 26: Decision Support).

Because energy systems in the United States are not centrally planned, they tend to reflect energy decisions shaped by law, regulation, other policies, and economic, technological, and other factors in markets. Trends in use patterns may continue into the future; this is an opportunity to increase resilience but also a major uncertainty for energy utilities and policy makers. Energy infrastructure tends to be long-lived, so resiliency can be enhanced by more deliberate applications of risk-management techniques and information about anticipated climate impacts and trends.[38]

For example, risk-management approaches informed by evolving climate conditions could be used to project the value of research and development on, or investments in, construction of dikes and barriers for coastal facilities or for dry-cooling technologies for power plants in regions where water is already in short supply. Solar and wind electricity generation facilities could be sited in areas that are initially more expensive (such as offshore areas) but less subject to large reductions in power plant output resulting from climatic changes. Targets for installed reserve margins for electric generating capacity and capacity of power lines can be established using certain temperature expectations, but adjusted as conditions unfold over time.

A range of climate change impacts will affect future energy production. This table shows possible ways to anticipate and respond to these changes. Innovations in technologies may provide additional opportunities and benefits to these and other adaptation actions. Behavioral change by consumers can also promote resiliency.

Table 4.2 summarizes actions that can be taken to increase the ease with which energy systems can adjust to climate change. Many of these adaptation investments entail "no regrets" actions, providing short-term benefits because they address current vulnerabilities as well as future risks.

Possible Climate Resilience and Adaptation Actions in Energy Sector				
	Key Challenges Addressed			
Possible Actions	**Extreme Weather Events**	**Increase in Peak Energy Loads**	**Water Constraints on Energy Production**	**Sea Level Rise**
Supply: System and Operational Planning				
Diversifying supply chains	X	X	X	X
Strengthening and coordinating emergency response plans	X	X	X	
Providing remote/protected emergency-response coordination centers	X			
Developing flood-management plans or improving stormwater management	X			X
Developing drought-management plans for reduced cooling flows			X	
Developing hydropower management plans/policies addressing extremes			X	
Supply: Existing Equipment Modifications				
Hardening/building redundancy into facilities	X	X		
Elevating water-sensitive equipment or redesigning elevation of intake structures	X			X
Building coastal barriers, dikes, or levees	X			X
Improving reliability of grid systems through back-up power supply, intelligent controls, and distributed generation	X	X	X	
Insulating equipment for temperature extremes	X			
References to technical studies with case studies on many of these topics may be found in Wilbanks et al. 2012.[4]				
Implementing dry (air-cooled) or low-water hybrid (or recirculating) cooling systems for power plants			X	
Adding technologies/systems to pre-cool water discharges			X	
Using non-fresh water supplies: municipal effluent, brackish or seawater			X	
Relocating vulnerable facilities	X		X	X
Supply: New Equipment				
Adding peak generation, power storage capacity, and distributed generation	X	X	X	X
Adding back-up power supply for grid interruptions	X	X	X	
Increasing transmission capacity within and between regions	X	X	X	X
Use: Reduce Energy Demand				
Improving building energy, cooling-system and manufacturing efficiencies, and demand-response capabilities (for example, smart grid)	X	X		
Setting higher ambient temperatures in buildings	X	X		
Improving irrigation and water distribution/reuse efficiency		X	X	
Allowing flexible work schedules to transfer energy use to off-peak hours		X		

Table 4.3. Increased temperatures, changing precipitation patterns, and sea level rise will affect many sectors and regions, including energy production, agriculture yields, and infrastructure damage. Changes are also projected to affect hydropower, solar photovoltaic, and wind power, but the projected impacts are not well defined at this time.

Energy Supply: Summary of National and Regional Impacts, Challenges, and Opportunities							
Consequences[a]: Challenges and Opportunities							
	Fuel Extraction, Production and Refining		Fuel Distribution Transport/ Pipelines	Electricity Generation			Electricity Distribution
	Hydrocarbons[b]	Biofuels		Thermal Power Generation[c]			
Physical Impacts – High Likelihood	Increased Ambient Temperature of Air and Water	Increased Extremes in Water Availability	Coastal Erosion and Sea Level Rise	Increased Ambient Temperature of Air and Water	Increased Extremes in Water Availability	Coastal Erosion and Sea Level Rise	Hot Summer Periods
National Trend Summary[f] Consequence	Decreased Production and Refining Capacity	Decreased Agricultural Yields	Damage to Facilities	Reduced Plant Efficiency and Cooling Capacity	Interruptions to Cooling Systems	Damage to Facilities	Reduced Capacity/Damage to Lines
Key Indicator (2071-2099 vs. 1971-2000)	**Mean Annual Temperature[d]**	**Summer Precipitation[d]**	**Sea level Rise[e] (2100)**	**Mean Annual Temperature[d]**	**Summer Precipitation[d]**	**Sea Level Rise[e] (2100)**	**# Days>90°F[f,g] (2055)**
Northeast	+4°F to 9°F	-5% to +6%	1.6–3.9 ft (0.5–1.2m)	+4°F to 9°F	-5% to +6%	1.6–3.9 ft. (0.5–1.2m)	+13 days
Southeast	+3°F to 8°F	-22% to +10%		+3°F to 8°F	-22% to +10%		+31 days
Midwest	+4°F to 10°F	-22% to +7%		+4°F to 10°F	-22% to +7%		+19 days
Great Plains	+3°F to 9°F	-27% to +5%		+3°F to 9°F	-27% to +5%		+20 days
Southwest	+4°F to 9°F	-13% to +3%		+4°F to 9°F	-13% to +3%		+24 days
Northwest	+3°F to 8°F	-34% to -4%		+3°F to 8°F	-34% to -4%		+4 days
Alaska	+4°F to 9°F	+10% to +25%		+4°F to 9°F	+10% to +25%		No Projection
Pacific Islands	+2°F to 5°F	Range from little change to increases		+2°F to 5°F	Range from little change to increases		No Projection

Notes

a) Excludes extreme weather events.

b) Hydrocarbons include coal, oil, and gas including shales.

c) Thermal power generation includes power plants fired from nuclear, coal, gas, oil, biomass fuels, solar thermal, and geothermal energy.

d) CMIP3 15 GCM Models: 2070–2099 Combined Interquartile Ranges of SRES B1 and A2 (versus 1971–2000), incorporating uncertainties from both differences in model climate sensitivity and differences between B1 and A2 in emissions trajectories

e) Range of sea level rise for 2100 is the Low Intermediate to High Intermediate Scenario from "Sea Level Change Scenarios for the U.S. National Climate Assessment."[35] Range is similar to the 1 to 4 feet of sea level rise projected in Ch. 2: Our Changing Climate, Key Message 10. There will be regional variations in sea level rise, and this category of impacts does not apply for the Midwest region.

f) 2055 NARCCAP

g) References:[4,25]

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PHOTO CREDITS

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:
The author team met bi-weekly by teleconference during the months of March through July 2012. Early in the development of key messages and a chapter outline, the authors reviewed all of the four dozen relevant technical input reports that were received in response to the Federal Register solicitation for public input. Selected authors participated in a U.S. Department of Energy (DOE) sponsored workshop on Energy Supply and Use, December 29-30, 2011, in Washington, D.C. The workshop was organized specifically to inform a DOE technical input report and this National Climate Assessment and to engage stakeholders in this process. The authors selected key messages based on the risk and likelihood of impacts, associated consequences, and available evidence. Relevance to decision support within the energy sector was also an important criterion.

The U.S. maintains extensive data on energy supply and use. The Energy Information Administration (EIA) of the U.S. Department of Energy is a primary organization in this activity, and data with quality control, quality assurance, and expert review are available through EIA Web pages (for example, EIA 2012, EIA 2013[39]).

KEY MESSAGE #1 TRACEABLE ACCOUNT

Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of certain types of extreme weather events are expected to change.

Description of evidence base
A series of NCA workshops reviewed potential influences of climate change thus far on the frequency and intensity of certain types of extreme events.[3] Numerous past extreme events demonstrate damage to energy facilities and infrastructure. Data assembled and reviewed by the Federal Government summarize typical costs associated with damage to energy facilities by extreme events.[5] State and regional reports as well as data provided by public utilities document specific examples.[4,9,10,26] Damage to Gulf Coast energy facilities and infrastructure by Hurricanes Katrina and Rita in 2005 provides excellent examples to support this key message.[8,9] Wildfire also damages transmission grids.[10]

The authors benefited from Agency-sponsored technical input reports summarizing relevant data and information on energy supply and use as well as urban systems and infrastructure.[4,21,25] A number of other technical input reports were relevant as well. These were reviewed carefully, particularly with regard to the identification of key messages.

New information and remaining uncertainties
The information provided through a series of NCA workshops provided new (and current) evidence for influences of climate change on the frequency and intensity of extreme events. The summaries from those workshops provide succinct evidence that certain extreme events that damage energy facilities and infrastructure can be expected to increase in number and intensity with climate change (for example, Peterson et al. 2012[3]). Documentation of damage to energy facilities and infrastructure continues to accumulate, increasing confidence in this key message.[5,14]

The regional and local character of extreme events varies substantially, and this variability is a source of significant uncertainty regarding the impacts of climate change and consequences in terms of damage to energy facilities by extreme events. Additionally, damage to energy infrastructure in a specific location can have far-reaching consequences for energy production and distribution, and synthesis of such indirect consequences for production and distribution does not yet support detailed projections.

Assessment of confidence based on evidence
High. There is high consensus with moderate evidence that extreme weather events associated with climate change will increase disruptions of energy infrastructure and services in some locations.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the energy supply and use technical input.[4] Global climate models simulate increases in summer temperatures, and the NCA climate scenarios[2,20] describe this aspect of climate change projections for use in preparing this report (Ch. 2: Our Changing Climate). Data used by Kunkel et al.[2] and Census Bureau population data, synthesized by the EIA,[15] were the basis for calculating population-weighted heating and cooling degree-days over the historic period as well as projections assuming SRES B1 and A2 scenarios.

The NCA climate scenarios[2] project an increase in the number of cooling days and decrease in heating days, with peak electricity demand in some regions shifting from winter to summer[27] and shifting to electricity needs for cooling instead of fossil fuels for heating.[25,26,27]

New information and remaining uncertainties

While there is little uncertainty that peak electricity demands will increase with warming by climate change, substantial regional variability is expected. Climate change projections do not provide sufficient spatial and temporal detail to fully analyze these consequences. Socioeconomic factors including population changes, economic conditions, and energy prices, as well as technological developments in electricity generation and industrial equipment, will have a strong bearing on electricity demands, specific to each region of the country.

Assessment of confidence based on evidence

High.Assuming specific climate change scenarios, the consequences for heating and cooling buildings are reasonably predictable, especially for the residential sector. With a shift to higher summer demands for electricity, peak demands for electricity can be confidently expected to increase.

Key message #3 Traceable Account

Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production.

Description of evidence base

Climate scenarios prepared for the NCA[2] describe decreases in precipitation under the SRES A2 scenario, with the largest decreases across the Northwest and Southwest in the spring and summer.

Technical input reports (for example, Wilbanks et al.[4,21]) summarize data and studies show that changes in water availability will affect energy production,[33] and more specifically, that water shortages will constrain electricity production (Ch. 2: Our Changing Climate).[29,32] The impacts of drought in Texas during 2011 are an example of the consequences of water shortages for energy production as well as other uses (Ch. 10: Energy, Water, and Land). Electric utility industry reports document potential consequences for operation of generating facilities.[34] A number of power plants across the country have experienced interruptions due to water shortages.

New information and remaining uncertainties

An increasing number of documented incidents of interruptions in energy production due to water shortages provide strong evidence that decreased precipitation or drought will have consequences for energy production.[21]

There is little uncertainty that water shortages due to climate change will affect energy production. But uncertainty about changes in precipitation and moisture regimes simulated by global climate models is significantly higher than for simulated warming. Additionally, climate change simulations lack the spatial and temporal detail required to analyze the consequences for water availability at finer scales (for example, local and regional). Finer-scale projections would be relevant to decisions about changes in energy facilities to reduce risk or adapt to water shortages associated with climate change.

Assessment of confidence based on evidence

High. The evidence is compelling that insufficient water availability with climate change will affect energy production; however, simulations of climate change lack the detail needed to provide more specific information for decision support.

KEY MESSAGE #4 TRACEABLE ACCOUNT

In the longer term, sea level rise, extreme storm surge events, and high tides will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

Description of evidence base

The sea level change scenario report prepared for the NCA (see also Ch. 2: Our Changing Climate)[35] provides further information about sea level change. Extreme surge events at high tides are expected to increase,[11] raising the risk of inundating energy facilities such as power plants, refineries, pipelines, and transmission and distribution networks (for example, Sathaye et al. 2013[10]) Data available through the EIA (for example, EIA 2010[15] provide high-quality information about the locations and distribution of energy facilities.

A substantial portion of the nation's energy facilities and infrastructure are located along coasts or offshore, and sea level rise will affect these facilities (Ch. 25: Coasts; Ch. 17: Southeast; Ch. 5: Transportation).[4,10,21,36]

New information and remaining uncertainties

Projections of sea level change are relatively uncertain compared to other aspects of climate change. More importantly, there will be substantial regional and local variability in sea level change, and facilities in locations exposed to more frequent and intense extreme wind and precipitation events will be at higher risk. Data and analyses to understand regional and local sea level change are improving, but substantial uncertainty remains and decision support for adaptation is challenged by these limitations.

Assessment of confidence based on evidence

High. There is high confidence that increases in global mean sea level, extreme surge events, and high tides will affect coastal energy facilities; however, regional and local details are less certain.

KEY MESSAGE #5 TRACEABLE ACCOUNT

As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways. Depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.

Description of evidence base

A number of studies describe U.S. energy system configurations in terms of supply and use assuming different scenarios of climate change, including SRES B1 and A2.[14,25,34] A technical input report to the NCA by DOE[4,21] provides details and updates earlier studies. The potential role of biofuels is described within chapters 6 and 7 of this report (Ch. 6: Agriculture; Ch. 7: Forests).

New information and remaining uncertainties

Understanding of options for future energy supply and use within the U.S. improves, as the EIA and other organizations update data and information about U.S. energy systems as well as projections of the mix of primary energy under various assumptions about demographic, economic, and other factors. With additional data and better models, alternative energy mixes can be explored with respect to climate change adaptation and mitigation. But numerous factors that are very difficult to predict – financial, economic, regulatory, technological – affect the deployment of actual facilities and infrastructure.

Assessment of confidence based on evidence

High. Given the evidence about climate change impacts and remaining uncertainties associated with the future configuration of energy systems and infrastructure, there is high confidence that U.S. energy systems will evolve in ways that affect risk with respect to climate change and options for adaptation or mitigation.

Climate Change Impacts in the United States

CHAPTER 5
TRANSPORTATION

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5 TRANSPORTATION

KEY MESSAGES

1. **The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways.**
2. **Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.**
3. **Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.**
4. **Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.**

The U.S. economy depends on the personal and freight mobility provided by the country's transportation system. Essential products and services like energy, food, manufacturing, and trade all depend in interrelated ways on the reliable functioning of these transportation components. Disruptions to transportation systems, therefore, can cause large economic and personal losses.[1] The national transportation system is composed of four main components that are increasingly vulnerable to climate change impacts:

- fixed node infrastructure, such as ports, airports, and rail terminals;
- fixed route infrastructure, such as roads, bridges, pedestrian/bicycle trails and lanes, locks, canals/channels, light rail, subways, freight and commuter railways, and pipelines, with mixed public and private ownership and management;
- vehicles, such as cars, transit buses, and trucks; transit and railcars and locomotives; ships and barges; and aircraft – many privately owned; and
- the people, institutions, laws, policies, and information systems that convert infrastructure and vehicles into working transportation networks.

Besides being affected by climate changes, transportation systems also contribute to changes in the climate through emissions. In 2010, the U.S. transportation sector accounted for 27% of total U.S. greenhouse gas emissions, with cars and trucks accounting for 65% of that total.[2] Petroleum accounts for 93% of the nation's transportation energy use.[2] This means that policies and behavioral changes aimed at reducing greenhouse gas emissions will have significant implications for the various components of the transportation sector.

Weather events influence the daily and seasonal operation of transport systems.[3,4,5] Transportation systems are already experiencing costly climate change related impacts. Many inland states – for example, Vermont, Tennessee, Iowa, and Missouri – have experienced severe precipitation events, hail, and flooding during the past three years, damaging roads, bridges, and rail systems and the vehicles that use them. Over the coming decades, all regions and modes of transportation will be affected by increasing temperatures, more extreme weather events, and changes in precipitation. Concentrated transportation impacts are likely in Alaska and along seacoasts.

Climate trends affect the design of transport infrastructure, which is expensive and designed for long life (typically 50 to 100 years). The estimated value of U.S. transportation facilities in 2010 was $4.1 trillion.[6] As climatic conditions shift, portions of this infrastructure will increasingly be subject to climatic stresses that will reduce the reliability and capacity of transportation systems.[7] Transportation systems are also vulnerable to interruptions in fuel and elec-


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tricity supply, as well as communications disruptions – which are also subject to climatic stresses.[7,8] For example, power outages resulting from Hurricane Katrina shut down three major petroleum pipelines for two days, and the systems operated at reduced capacities for two weeks.[9]

Climate change will affect transportation systems directly, through infrastructure damage, and indirectly, through changes in trade flows, agriculture, energy use, and settlement patterns. If, for instance, corn cultivation shifts northward in response to rising temperatures, U.S. agricultural products may flow to markets from different origins by different routes.[10] If policy measures and technological changes reduce greenhouse gas emissions by affecting fuel types, there will likely be significant impacts on the transportation of energy supplies (such as pipelines and coal trains) and on the cost of transportation to freight and passenger users.[11]

Shifts in demographic trends, land-use patterns, and advances in transportation technology over the next few decades will have profound impacts on how the nation's transportation system functions, its design, and its spatial extent. As transportation officials shape the future transportation system to address new demands, future climate conditions should be considered as part of the planning and decision-making process.

Disruptions to transportation system capacity and reliability can be partially offset by adaptations. Transportation systems *as networks* may use alternative routes around damaged elements or shift traffic to undamaged modes. Other adaptation actions include new infrastructure designs for future climate conditions, asset management programs, at-risk asset protection, operational changes, and abandoning/relocating infrastructure assets that would be too expensive to protect.[12] As new and rehabilitated transportation systems are developed, climate change impacts should be routinely incorporated into the planning for these systems.

There will be challenges in adapting transportation systems to climate related changes, particularly when factoring in projected growth in the transportation sector. A National Surface Transportation Policy and Revenue Commission in 2007 forecast the following annual average growth rates: average annual tonnage growth rates of 2.1% for trucks, 1.9% for rail, and 1.2% for waterborne transportation, and an average annual passenger vehicle miles traveled growth rate of 1.82% through 2035 and 1.72% through 2055.[13]

Key Message 1: Reliability and Capacity at Risk

The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways.

Global climate change has both gradual and extreme event implications. A gradually warming climate will accelerate asphalt deterioration and cause buckling of pavements and rail lines.[14] Streamflows based on increasingly more frequent and intense rainfall instead of slower snowmelt could increase the likelihood of bridge damage from faster-flowing streams.[15] However, less snow in some areas will reduce snow removal costs and extend construction seasons. Shifts in agricultural production patterns will necessitate changes in transportation routes and modes.[16]

Climate models project that extreme heat and heat waves will become more intense, longer lasting, and more frequent (Ch. 2: Our Changing Climate). By 2080-2100, average temperatures are expected to increase by 3°F to 6°F for the continental United States, assuming emissions reductions from current trends (B1 scenario), while continued increases in emissions (A2 scenario) would lead to an increase in average temperatures ranging from 5°F in Florida to 9°F in the upper Midwest.[17]

The impact on transportation systems not designed for such extreme temperatures would be severe. At higher temperatures, expansion joints on bridges and highways are stressed and some asphalt pavements deteriorate more rapidly.[18] Rail

THAWING ALASKA

Permafrost – soil saturated with frozen water – is a key feature of the Alaskan landscape. *Frozen* permafrost is a suitable base for transportation infrastructure such as roads and airfields. In rapidly warming Alaska, however, as permafrost thaws into mud, road shoulders slump, highway cuts slide, and runways sink. Alaska currently spends an extra $10 million per year repairing permafrost damage.[25]

A recent study, which examined potential climate damage to Alaskan public infrastructure using results from three different climate models,[26] considered 253 airports, 853 bridges, 131 harbors, 819 miles of railroad, 4,576 miles of paved road, and 5,000 miles of unpaved road that could be affected by climate change. The present value of additional public infrastructure costs due to climate change impacts was estimated at $5.6 to $7.6 billion through 2080, or 10% to 12% of total public infrastructure costs in Alaska. These costs might be reduced by 40% with strong adaptation actions.[26]

track stresses and track buckling will increase.[14,19] High air temperatures can affect aircraft performance; lift-off limits at hot-weather and high-altitude airports will reduce aircraft operations.[20]

Construction crews may have to operate on altered time schedules to avoid the heat of the day, with greater safety risks for workers.[21] The construction season may lengthen in many localities. Similarly, higher temperatures (and precipitation changes) are likely to affect transit ridership, bicycling, and walking.[14,22]

Climate change is most pronounced at high northern latitudes. Alaska has experienced a 3°F rise in average temperatures since 1949,[23] double the rest of the country. Winter temperatures have risen by 6°F.[23] On the North Slope, sea ice formerly provided protection to the shoreline against strong fall/winter winds and storms (see Ch. 12: Indigenous Peoples). Retreating ice reduces this protection, eroding the shoreline and endangering coastal villages. Thawing permafrost is causing pavement, runway, rail, and pipeline displacements, creating problems for operation and maintenance, and requiring reconstruction of key facilities.

Arctic warming is also projected to allow the seasonal opening of the Northwest Passage to freight shipment.[24] Global climate projections to 2100 show extensive open water areas during the summer around the Arctic basin. Retreat of Arctic sea ice has been observed in all seasons over the past five decades, with the most prominent retreat in summer.[24] This has allowed a limited number of freighters, cruise ships, and smaller vessels to traverse the Northwest Passage for several years.

Possible Future Flood Depths in Mobile, AL with Rising Sea Level

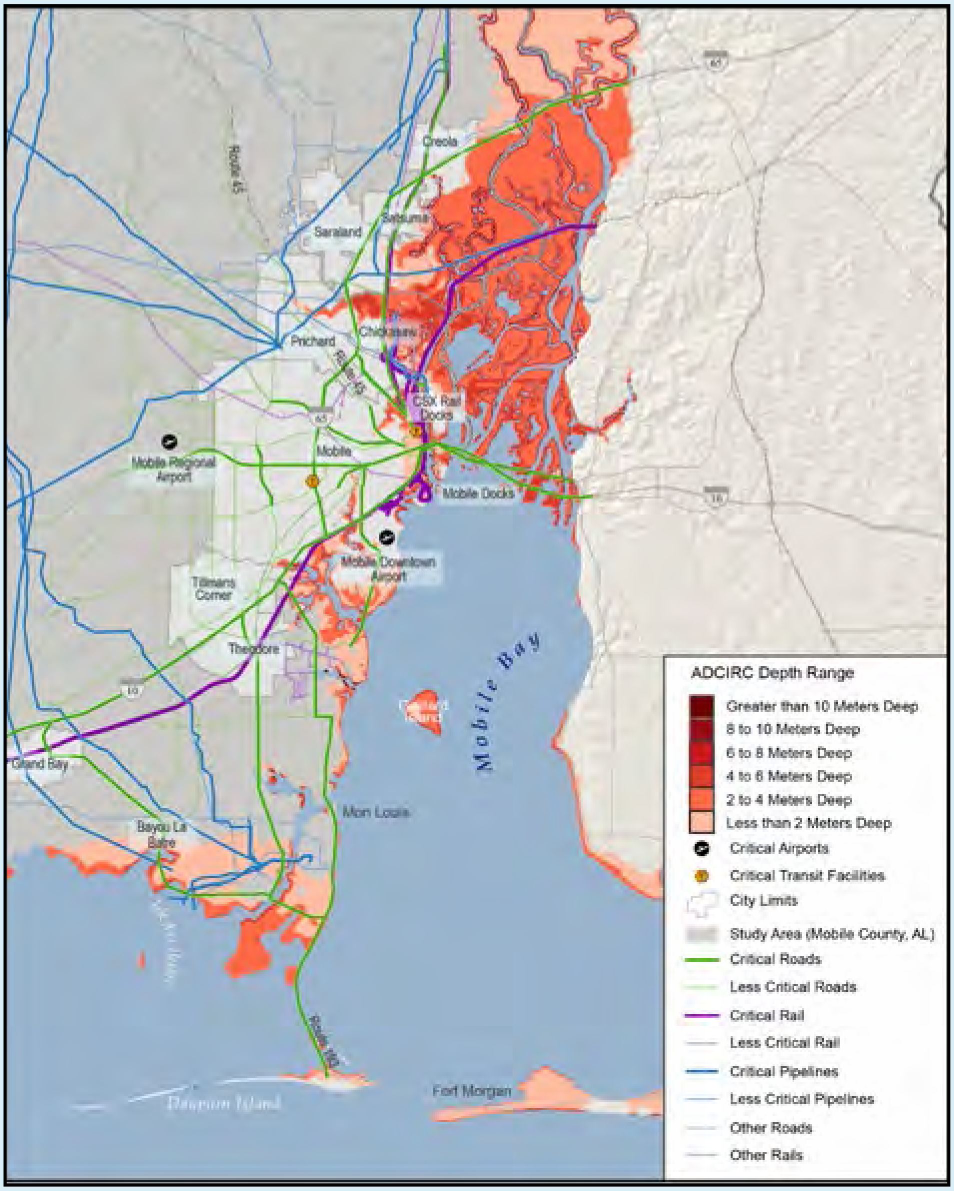

Figure 5.1. Many coastal areas in the United States, including the Gulf Coast, are especially vulnerable to sea level rise impacts on transportation systems.[11,27,28] This is particularly true when one considers the interaction among sea level rise, wave action, and local geology.[29] This map shows that many parts of Mobile, Alabama, including critical roads, rail lines, and pipelines, would be exposed to storm surge under a scenario of a 30-inch sea level rise combined with a storm similar to Hurricane Katrina. Not all roads would be flooded if they merely run through low areas since some are built above flood levels. A 30-inch sea level rise scenario is within the range projected for global sea level rise (Ch. 2: Our Changing Climate, Key Message 10). (Figure source: U.S. Department of Transportation 2012[30]).

Key Message 2: Coastal Impacts

Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.

The transportation impacts of rising global sea level, which is expected to continue to rise by an additional 1 to 4 feet by 2100 (see also Ch. 2: Our Changing Climate, Key Message 10),[31] will vary widely by location and geography. When sea level rise is coupled with intense storms, the resulting storm surges will be greater, extend farther inland, and cause more extensive damage. Relative sea level rise will be greater along some coasts (such as Louisiana, Texas, and parts of the Chesapeake Bay), and this will have significant effects on transportation infrastructure, even without the coupling with storms, due to regional land subsidence (land sinking or settling) (Ch. 25: Coasts). Ports and harbors will need to be reconfigured to accommodate higher seas. Many of the nation's largest ports are along the Gulf Coast, which is especially vulnerable due to a combination of sea level rise, storm surges, erosion, and land subsidence.[11] Two additional impacts for ports include 1) as sea level rises, bridge clearance may not be adequate to allow safe passage of large vessels; 2) even if the elevation of port facilities is adequate, any main access road that is not elevated will become more frequently inundated, thus affecting port operations. In 2011, the United States imported 45% of all oil consumed, and 56% of those imports passed through Gulf Coast ports.[32]

More frequent disruptions and damage to roads, tracks, runways, and navigation channels are projected in coastal areas beyond the Gulf Coast. Thirteen of the nation's 47 largest airports have at least one runway with an elevation within 12 feet of current sea levels.[33] Most ocean-going ports are in low-lying coastal areas, including three of the most important for imports and exports: Los Angeles/Long Beach (which handles 31% of the U.S. port container movements) and the Port of South Louisiana and the Port of Galveston/Houston (which combined handle 25% of the tonnage handled by U.S. ports).[34] Extreme floods and storms associated with climate change will lead to increased movement of sediment and buildup of sandy formations in channels. For example, many federally maintained navigation channels have deteriorated in recent years to dimensions less than those authorized, in part due to floods and storms, which resulted in reduced levels of service that affect navigation safety and reliability.[35] Channels that are not well maintained and have less sedimentation storage volume will thus be more vulnerable to significant, abrupt losses in navigation service levels. Additional channel storage capacity that may be created by sea level rise will also increase water depths and increase sedimentation in some channels. (See Ch. 25: Coasts for additional discussion of coastal transportation impacts.)

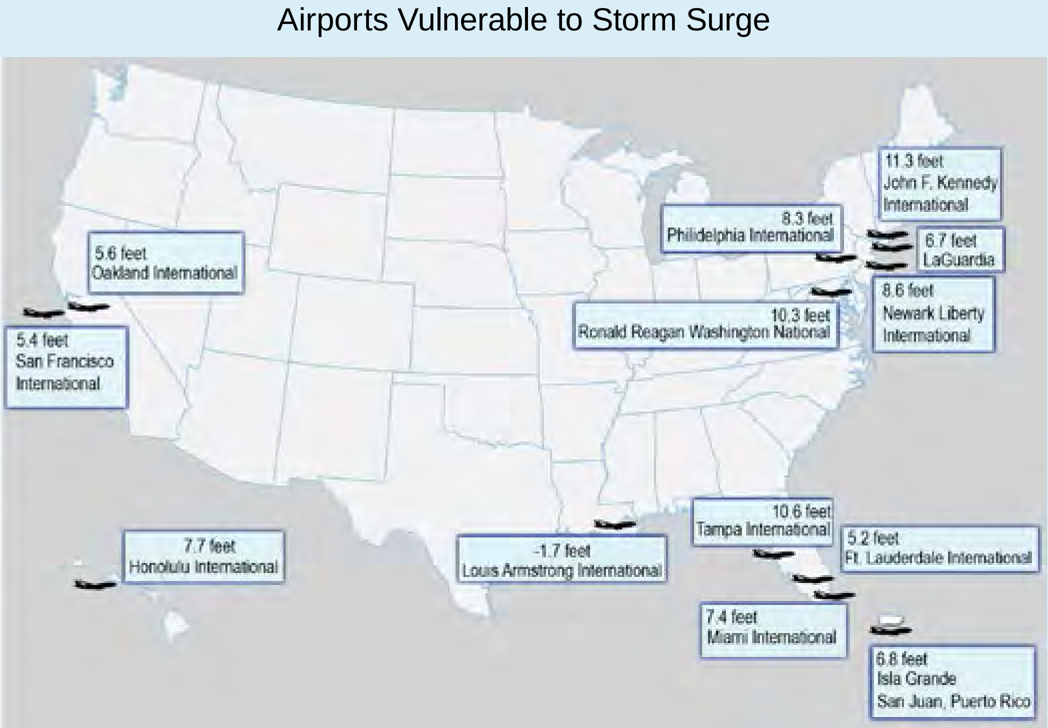
Airports Vulnerable to Storm Surge

Figure 5.2. Thirteen of the nation's 47 largest airports have at least one runway with an elevation within the reach of moderate to high storm surge. Sea level rise will pose a threat to low-lying infrastructure, such as the airports shown here. (Data from Federal Aviation Administration 2012[33]).

Key Message 3: Weather Disruptions

Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.

Changes in precipitation patterns, particularly more extreme precipitation events and drought, will affect transportation systems across the country. Delays caused by severe storms disrupt almost all types of transportation. Storm drainage systems for highways, tunnels, airports, and city streets could prove inadequate, resulting in localized flooding. Bridge piers are subject to scour as runoff increases stream and river flows, potentially weakening bridge foundations. Severe storms will disrupt highway traffic, leading to more accidents and delays. More airline traffic will be delayed or canceled.


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Infrastructure around the country has been compromised by extreme weather events such as heavy downpours. Road and bridge damage are among the infrastructure failures that have occurred during these extreme events.

Inland waterways may well experience greater floods, with high flow velocities that are unsafe for navigation and that cause channels to shut down intermittently. Numerous studies indicate increasing severity and frequency of flooding throughout much of the Mississippi and Missouri River Basins.[36] Increases in flood risk reflect both changing precipitation and changing land-use patterns.[37] In the Upper Mississippi/Missouri Rivers, there have been two 300- to 500-year floods over the past 20 years.[38] Drought increases the probability of wildfires, which affect visibility severely enough to close roads and airports. Drought can lower vessel drafts on navigable rivers and associated lock and dam pools. On the other hand, less ice formation on navigable waterways has the potential to increase seasonal windows for passage of navigation.

Gulf Coast Transportation Hubs at Risk

Figure 5.3. Within this century, 2,400 miles of major roadway are projected to be inundated by sea level rise in the Gulf Coast region. The map shows roadways at risk in the event of a sea level rise of about 4 feet, which is within the range of projections for this region in this century (see also Ch. 2: Our Changing Climate, Key Message 10). In total, 24% of interstate highway miles and 28% of secondary road miles in the Gulf Coast region are at elevations below 4 feet. (Figure source: Kafalenos et al. 2008[39]).

The frequency of the strongest hurricanes (Category 4 and 5) in the Atlantic is expected to increase (see Ch. 2: Our Changing Climate, Key Message 8). As hurricanes approach landfall, they create storm surge, which carries water farther inland. The resulting flooding, wind damage, and bridge destruction disrupts virtually all transportation systems in the affected area. Many of the nation's military installations are in areas that are vulnerable to extreme weather events, such as naval bases located in hurricane-prone zones.

HURRICANE SANDY

On October 29, 2012, Hurricane Sandy dealt the transportation systems of New Jersey and New York and environs a massive blow (See also Ch.16: Northeast, "Hurricane Vulnerability"; Ch. 11: Urban "Hurricane Sandy"). The damages from Sandy are indicative of what powerful tropical storms and higher sea levels could bring on a more frequent basis in the future and were very much in line with vulnerability assessments conducted over the past four years.[40,41,42] All tunnels and most bridges leading into New York City were closed during the storm. Storm tides of up to 14 feet[43] flooded the Queens Midtown, Holland, and Carey (Brooklyn Battery) tunnels, which remained closed for at least one week (two weeks for the Carey Tunnel) while floodwaters were being pumped out and power restored. The three major airports (Kennedy, Newark, and LaGuardia) flooded, with LaGuardia absorbing the worst impact and closing for three days.[44]

Hurricane Sandy Causes Flooding in New York City Subway Stations

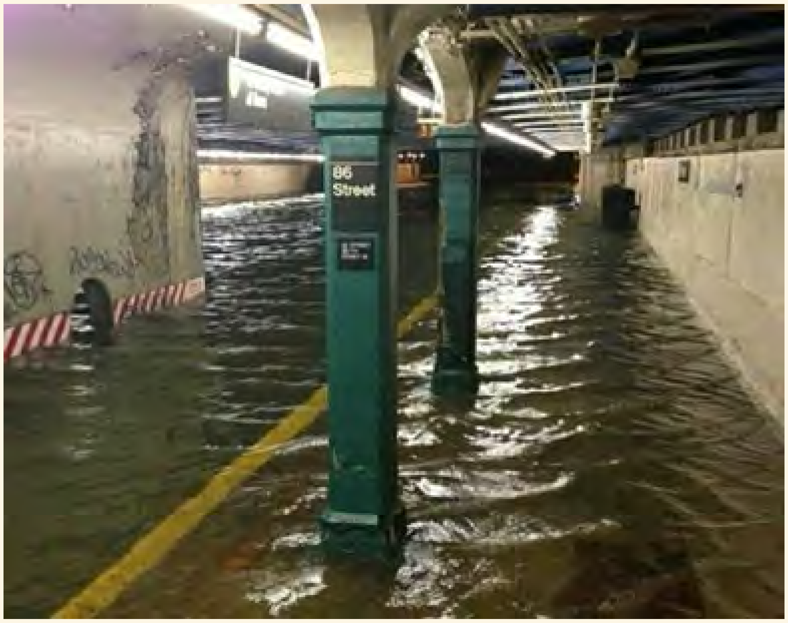

Figure 5.4. The nation's busiest subway system sustained the worst damage in its 108 years of operation on October 29, 2012, as a result of Hurricane Sandy. Millions of people were left without service for at least one week after the storm, as the Metropolitan Transportation Authority rapidly worked to repair extensive flood damage (Photo credit: William Vantuono, Railway Age Magazine, 2012[46]).

Almost 7.5 million passengers per day ride the New York City subways and buses.[45] Much of the New York City subway system below 34th Street was flooded, including all seven tunnels under the East River to Brooklyn and Queens. In addition to removing the floodwaters, all electrical signaling and power systems (the third rails) had to be cleaned, inspected, and repaired. Service on most Lower Manhattan subways was suspended for at least one week,[46] as was the PATH system to New Jersey.[47] Commuter rail service to New Jersey, Long Island, and northern suburbs, with more than 500,000 passengers per day,[45] was similarly affected for days or weeks with flooded tunnels, downed trees and large debris on tracks, and loss of electrical power.[48] In addition, miles of local roads, streets, underpasses, parking garages, and bridges flooded and/or were badly damaged in the region, and an estimated 230,000 parked vehicles[49] sustained water damage. Flooded roadways prevented the New York Fire Department from responding to a fire that destroyed more than 100 homes in Brooklyn's Breezy Point neighborhood.[50]

Hurricane Sandy's storm surge produced nearly four feet of floodwaters throughout the Port of New York and New Jersey, damaging electrical systems, highways, rail track, and port cargo; displacing hundreds of shipping containers; and causing ships to run aground.[51] Floating debris, wrecks, and obstructions in the channel had to be cleared before the Port was able to reopen to incoming vessels within a week.[52] Pleasure boats were damaged at marinas throughout the region. On a positive note, the vulnerability analyses prepared by the metropolitan New York authorities and referenced above provided a framework for efforts to control the damage and restore service more rapidly. Noteworthy are the efforts of the Metropolitan Transportation Authority to protect vital electrical systems and restore subway service to much of New York within four days.

The impacts of this extraordinary storm on one of the nation's most important transportation nodes were felt across the country. Airline schedules throughout the United States and internationally were snarled; Amtrak rail service along the East Coast and as far away as Buffalo and Montreal was curtailed; and freight shipments in and out of the hurricane impact zone were delayed. The resultant direct costs to the community and indirect costs to the economy will undoubtedly rise into the tens of billions of dollars (See also Ch. 11: Urban, "Hurricane Sandy").

Table 5.1 relates to overall national expectations based on Angel and Kunkel 2010[54] and as postulated by chapter authors. This kind of matrix is likely to be most valuable and accurate if used at the state/regional/local levels. (Source: Matrix format adapted from McLaughlin et al. 2011[53]).

Illustrative Risks of Climate-related Impacts

		Likelihood of Occurrence			
		Low	**Medium**	**High**	**Virtually Certain**
Magnitude of Consequences	**High**	Subway and tunnel flooding	Increased widespread flooding of transportation facilities	Major localized flooding disrupts transportation systems	Inundation of coastal assets due to storm surge
	Medium	Increased rock/mud slides blocking road and rail facilities	Train derailment due to rail buckling	Increased disruption of barge traffic due to flooding	Short-term road flooding and blocked culverts due to extreme events
	Low	Lower visibility from wildfires due to drought conditions	Northward shift of agricultural production places more demand and stress on roads and systems not prepared for higher volumes	Pavement heaving and reduced pavement life due to high temperatures	Inundation of local roads due to sea level rise
	Positive (beneficial)	Reduced flight cancellations due to fewer blizzards	Reduced maintenance costs for highways and airports due to warmer winters	Reduced Great Lakes freezing, leading to longer shipping season	Longer seasonal opening of Northwest Passage

Risks and Consequences

Risk is a function of both likelihood of impact and the consequences of that impact. Table 5.1 is an illustrative application of a risk matrix adapted from the Port Authority of New York and New Jersey. As shown, different types of climate-related incidents/events can have associated with them a likelihood of occurrence and a magnitude of the consequences if the incident does occur.

In assessing consequences, the intensity of system use, as well as the existence or lack of alternative routes, must be taken into account. Disabling a transportation facility can have ripple effects across a network, with trunk (main) lines and hubs having the most widespread impacts.[53] Any comprehensive assessment of the consequences of climate change would need to encompass the broad array of factors that influence the nation's transportation system, and consider changes in population, society, technology, prices, regulation, and the economy that eventually affect transportation system performance.[55] For example, the trend in recent years in the U.S. economy of adopting just-in-time logistics increases the vulnerability of businesses to day-to-day disruptions caused by weather and flooding.

Key Message 4: Costs and Adaptation Options

Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.

Adaptation strategies can be employed to reduce the impact of climate change related events and the resulting consequences (see Ch. 28: Adaptation). Consideration of adaptation strategies in the transportation sector is especially important in the following five areas:

- **Transportation and land-use planning:** deciding what infrastructure to build and where to build it, as well as planning for vulnerable areas of the community and impacts on specific population groups.
- **Vulnerability and risk assessment**: identifying existing vulnerable facilities and systems, together with the expected consequences.
- **New infrastructure design**: adapting new infrastructure designs that anticipate changing environmental and operational conditions.
- **Asset management**: adapting existing infrastructure and operations that respond to current and anticipated conditions, including changed maintenance practices and retrofits.
- **Emergency response:** anticipating expected disruptions from extreme weather events, and developing emergency response capability.

Adaptation takes place at multiple levels, from individual households and private businesses to federal, state, and local governments. The impacts associated with climate change are not new, since flooding, storm surge, and extreme heat have long been challenges. What *is* new is the changing frequency, intensity, and location/geography of impacts and hazards.

Responding effectively to present and future environmental challenges enhances the resilience of communities. Examples

Role of Adaptive Strategies and Tactics in Reducing Impacts and Consequences

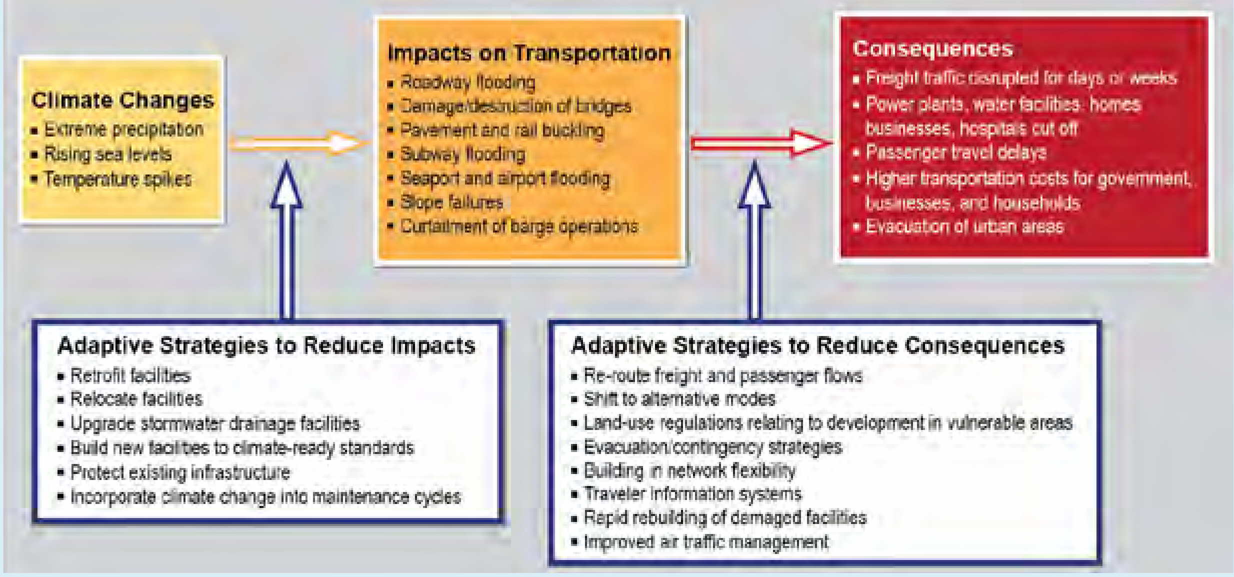

Figure 5.5. Many projected climate change impacts and resulting consequences on transportation systems can be reduced through a combination of infrastructure modifications, improved information systems, and policy changes.

include improvements in storm water management, coastal zone management, and coastal evacuation plans.

At the national level, the transportation network has some capability to adjust to climate-related disruptions due to the presence of network redundancy – multiple routes are often possible for long-distance travel, and more than one mode of transportation may be used for travel. However, in some cases, only one major route connects major destinations, such as Interstate 5 between Seattle and San Francisco; movements along such links are particularly vulnerable to disruption.

Disruptions to the nation's inland water system from floods or droughts can, and has, totally disrupted barge traffic. Severe droughts throughout the upper Midwest in 2012 reduced flows in the Missouri and Mississippi Rivers to near record low levels, disrupting barge traffic. While alternative modes, such as rail and truck, may alleviate some of these disruptions, it is impractical to shift major product shipments such as Midwest grain to other modes of transportation – at least in the near term.[57]

While extreme weather events will continue to cause flight cancellations and delays, many weather delays from non-extreme events are compounded by existing inadequacies in the current national air traffic management system.[58] Improvements in the air traffic system, such as those anticipated in the FAA's NextGEN (www.faa.gov/nextgen/), should reduce weather-related delays.

At the state and local level, there is less resilience to be gained by alternative routing, and impacts may be more intense. For example, significant local and regional disruption and economic costs could result from the flooding of assets as diverse as New York's subways, Iowa's roads, San Francisco's airports, and Vermont's bridges.

Climate change is one of many factors, and an increasingly important one, that many state, regional, and local agencies are considering as they plan for new and rehabilitated facilities. By incorporating climate change routinely into the planning process, governments can reduce the vulnerability to climate change impacts and take actions that enhance the resilience

WINTER STORM-RELATED CLOSURES OF I-5 AND I-90 IN WASHINGTON STATE, 2007-2008

In December 2007, heavy rainfall west of I-5, combined with melting snow from the mountains, created extremely high floodwaters in western Washington State. Six-hour rainfall amounts were near a 100-year event for areas in Southwest Washington. High winds, heavy rains, mudslides, and falling trees made travel unsafe on highways. Downed power lines blocked roads, and, in many urban areas, rainwater overwhelmed drainage systems and flooded roadways.

The combined economic impact in the I-5 and I-90 corridors was estimated at almost $75 million, of which some $47 million was associated with the I-5 disruption and $28 million with the I-90 corridor. Estimated highway damage from the winter storm was $18 million for state routes and another $39 million for city and county roads.[56]

PLANNING FOR CLIMATE CHANGE

Charlotte County exemplifies how local governments can incorporate aspects of climate change into transportation planning. The Metropolitan Planning Organization in Charlotte County-Punta Gorda, Florida conducted long-range scenario planning that integrated climate change projections.[65] A "smart growth" scenario that concentrated growth in urban centers was compared with a "resilient growth" scenario that steered development away from areas vulnerable to sea level rise. Planners evaluated the scenarios based on projected transportation performance outcomes and selected a preferred scenario reflecting aspects of each alternative.

of the transportation system to adverse weather conditions. Governments at various levels are already taking action, as described below.

Land-use planning can reduce risk by avoiding new development in flood-prone areas, conserving open space to enhance drainage, and relocating or abandoning structures or roads that have experienced repeated flooding. The National Flood Insurance Program encourages buyouts of repetitive loss structures and preservation of open space by reducing flood insurance rates for communities that adopt these practices.

An important step in devising an adaptation plan is to assess vulnerabilities (Ch. 26: Decision Support; Ch. 28: Adaptation). The Federal Highway Administration funded pilot projects in five coastal states to test a conceptual framework for evaluating risk.[59] The framework identifies transportation assets, evaluates the likelihood of impact on specific assets, and assesses the seriousness of such impacts.

Several state and local governments have conducted additional vulnerability assessments that identify potential impacts to transportation systems, especially in coastal areas. Detailed assessment work has been undertaken by New York City,[40,42,60] California,[61] Massachusetts,[62] Washington,[63] Florida, and Boston.[64]

Non-coastal states and regions have also begun to produce vulnerability assessments. Midwestern states, including Wisconsin[66] Iowa,[67] and Michigan,[68] have addressed increasing risk of flooded roadways and other impacts.

Transit systems are already implementing measures that reduce vulnerability to climate impacts, including rail buckling. Portland, Oregon's transit agency has been installing expansion joints at vulnerable locations, improving reliability of rail

TROPICAL STORM IRENE DEVASTATES VERMONT TRANSPORTATION IN AUGUST 2011

In August of 2011, Vermont was inundated with rain and massive flooding from Tropical Storm Irene (see also Ch.16: Northeast, "Hurricane Vulnerability"), closing down 146 segments of the state road system along with more than 200 bridges, and costing an estimated $175 to $200 million to rebuild state highways and bridges. An additional 2,000 or more municipal roads and nearly 1,000 culverts were damaged, and more than 200 miles of state-owned rail required repair.[75]

The volume of water was unprecedented, as was the power of the water in the rivers running through the state. Culverts and bridges were affected and slope stability was threatened as a result of the immense amount and power of water and subsequent flooding.

Tropical Storm Impact on Vermont Road

Figure 5.6. Vermont Route 131, outside Cavendish, a week after Tropical Storm Irene unleashed severe precipitation and flooding that damaged many Vermont roads, bridges, and rail lines. (Photo credit: Vermont Agency of Transportation).

When asked about the lessons learned, the Vermont Agency of Transportation (VTrans) indicated the importance of good maintenance of riverbeds as well as roads. VTrans is working with the Vermont Agency of Natural Resources, looking upstream and downstream at the structure of the rivers, recognizing that risk reduction may involve managing rivers as much as changing bridges or roadways.

Rich Tetreault of VTrans emphasized that "Certainly we will be looking to right-size the bridges and culverts that need to be replaced … Knowing that we do not have the funds to begin wholesale rebuilding of the entire highway network to withstand future flooding, we will also enhance our ability to respond" when future flooding occurs.[74]

Storm surge on top of rising sea levels have damaged roads and other coastal infrastructure.

AP Photo/The Virginian-Pilot, Steve Earley

service.[14] In New York, ventilation grates are being elevated to reduce the risk of flooding.[40]

Transportation agencies are incorporating climate change into ongoing design activities. For example, the Alaska Department of Transportation (DOT) spends more than $10 million annually on shoreline protection, relocations, and permafrost protection for roadways (see "Thawing Alaska").[25] In May 2011, the California Department of Transportation (Caltrans) issued guidance to their staff on whether and how to incorporate sea level rise into new project designs.[69]

States have begun to integrate climate impacts into Transportation Asset Management, a systematic process for monitoring the conditions of roads and transit facilities.[18,70] Maryland is working to prioritize assets taking sea level rise and increased storm intensity into account and is developing a tool to track assets and assess vulnerability.[71] Florida DOT continually monitors conditions on roads and bridges and is developing a statewide inventory and action plan for high-risk bridges.[72] Among inland states, Michigan DOT has identified a wide range of operational and asset management changes to adjust to climate change.[68] Planting street trees has been shown to reduce the urban heat island effect and reduce heat stress on pavement.[73]

Effective stormwater and stream/river management can reduce the risk of flooding for transportation infrastructure. Following Tropical Storm Irene, Vermont state agencies are working on stream and river management to reduce conditions that exacerbate flooding impacts on transportation.[74]

Effective asset management requires significant data and monitoring of transportation assets. Improved weather and road-condition information systems enable transportation system managers to anticipate and detect problems better and faster – enabling them to close systems if needed, alert motorists, and dispatch maintenance and snow-removal crews. As Michigan DOT has noted, an increase in lake-effect snows means that existing models used for snow and ice removal procedures are no longer reliable, requiring better monitoring and new models, as well as better roadway condition detection systems.[68]

Similarly, regular maintenance and cleaning of urban levee and culvert systems reduces the risk of roads and rails being inundated by flooding.

Extreme weather, such as hurricanes or intense storms, stresses transportation at precisely the time when smooth operation is critical. Effective evacuation planning, including early warning systems, coordination across jurisdictional boundaries, and creating multiple evacuation routes builds preparedness. Identifying areas with high concentrations of vulnerable and special-needs populations (including elderly, disabled, and transit-dependent groups) enhances readiness, as does identifying assets such as school buses or other transit vehicles that can be deployed for households that do not own vehicles.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

In developing key messages, the chapter author team engaged, via teleconference, in multiple technical discussions from January through May 2012 as they reviewed numerous peer reviewed publications. Technical input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. The author team's review included a foundational Technical Input Report for the National Climate Assessment, "Climate Impacts and U.S. Transportation."[57] Other published literature and professional judgment were also considered as the chapter key messages were developed. The chapter author team met in St. Louis, MO, in April 2012 for expert deliberation and finalization of key messages.

KEY MESSAGE #1 TRACEABLE ACCOUNT

The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways.

Description of evidence base

Climate impacts in the form of sea level rise, changing frequency of extreme weather events, heat waves, precipitation changes, Arctic warming, and other climatic conditions are documented in Ch. 2: Our Changing Climate of this report.

Climate can be described as the frequency distribution of weather over time. Existing weather conditions, flooding, and storm surge demonstrably affect U.S. transportation systems. By changing the frequency of these weather conditions, climate change will inevitably affect the reliability and capacity of U.S. transportations systems. This view is supported by multiple studies of the impacts of weather and climate change on particular transportation systems or particular regions.

An aggregate summary of impacts of climate change on U.S. transportation can be found in NRC 2008.[7] A paper commissioned for NRC 2008 considers specific impacts of various forms of climate change on infrastructure, for example, possible future constraints on infrastructure.[12] The effects of climate on transit systems are summarized in Hodges 2011.[14] The impact of heat and other climate effects on rail systems are described by Hodges 2011 and Rossetti 2002.[14,19]

Future impacts of sea level rise and other climatic effects on transportation systems in the Gulf Coast were examined by CCSP 2008.[11] The impacts of climate change on New York State, including its transportation system, were undertaken by Rosenzweig et al. 2011.[60] Impacts of sea level rise on transportation infrastructure for the mid-Atlantic were also discussed in CCSP 2009 SAP 4.1, Ch. 7.[27]

Weather impacts on road systems are discussed in "Climate Impacts and U.S. Transportation"[57] and numerous other sources. Weather impacts on aviation operations are discussed in Kulesa 200320 and numerous other sources.

In addition, the key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation."[57]

Additional peer-reviewed publications discuss the fact that Arctic warming is affecting existing Alaskan transportation infrastructure today, and is projected to allow the seasonal opening of the Northwest Passage to freight shipment.[24]

New information and remaining uncertainties

Recent changes in global sea level rise estimates documented in this report (Ch.2: Our Changing Climate, Key Message 10) have not been incorporated into existing regional studies of coastal areas. In addition, recent research by USGS on the interaction between sea level rise, wave action, and local geology have been incorporated in only a few studies.[29]

Specific estimates of climate change impacts on transportation are acutely sensitive to regional projections of climate change and, in particular, to the scale, timing, and type of predicted precipitation. New (CMIP5-based) regional climate projections will therefore affect most existing specific estimates of climate change impacts on transportation. Transportation planning in the face of uncertainties about regional-scale climate impacts presents particular challenges.

Impacts of climate on transportation system operations, including safety and congestion, both on road systems and in aviation, have been little studied to date.

Future characteristics of society, such as land-use patterns, demographics, and the use of information technology to alter transportation patterns, and possible changes to the very nature of future transportation systems themselves all create uncertainty in evaluating climate impacts on the nation's transportation networks. These societal changes will probably occur gradually, however, allowing the transportation systems to adapt. Adaptation can significantly ameliorate impacts on the transportation sector; however, evaluation of adaptation costs and strategies for the transportation sector is at a relatively early stage.

Assessment of confidence based on evidence
Confidence is **high** that transportation systems will be affected by climate change, given current climate projections, particularly regarding sea level rise and extreme weather events.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.

Description of evidence base
Estimates of global sea level rise are documented in Ch. 2: Our Changing Climate, Key Message 10 of this report.

The prospective impact of sea level rise and storm surge on transportation systems is illustrated by the impact of recent hurricanes on U.S. coastlines. In addition, research on impacts of sea level rise and storm surge on transportation assets in particular regions of the United States demonstrate the potential for major coastal impacts (for example, CCSP 2008, Rosenzweig et al. 2011, and Suarez et al. 2005[11,28,60]). Note that most existing literature on storm surge and sea level rise impacts on transportation systems is based on a global sea level rise of less than one meter (about 3 feet). The most recent projections include a potentially greater rise in global sea level (Ch. 2: Our Changing Climate, Key Message 10).

In addition, the key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation."[57]

New information and remaining uncertainties
As noted above, new estimates of global sea level rise have overtaken most of the existing literature on transportation and sea level rise in the United States. In addition, it is not clear that the existing transportation literature reflects recent USGS work on interactions between sea level rise, wave action, and local geology.[29]

New global sea level rise estimates will enable the development of new regional estimates, as well as revision of regional coastal erosion and flood modeling. Such smaller scale estimates are important because transportation and other infrastructure impacts must necessarily be studied in a local context.

Generally speaking, modeling of sea level rise impacts using existing USGS National Elevation Dataset (NED) data has well-understood limitations. Since NED data is freely and easily available, it is often used for preliminary modeling. More accurate and more recent elevation data may be captured via LIDAR campaigns, and this data collection effort will be necessary for accurate understanding of regional and local sea level rise and storm surge impacts.[27]

Accurate understanding of transportation impacts is specific to particular infrastructure elements, so detailed inventories of local and regional infrastructure must be combined with detailed and accurate elevation data and the best available predictions of local sea level rise and storm surge. Therefore, national assessments of sea level rise must be built on detailed local and regional assessments.

Improved modeling is needed on the interactions among sea level rise, storm surge, tidal movement, and wave action to get a better understanding of the dynamics of the phenomena.

Assessment of confidence based on evidence

The authors have **high** confidence sea levels are rising and storm surge on top of these higher sea levels pose risks to coastal transportation infrastructure.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation."[57]

Specific regional climate impacts can be identified in each NCA region of the country. Specific climate impacts on transportation by region include:

In Alaska, rising temperatures cause permafrost to melt, causing damage to roadbeds, airfields, pipelines, and other transportation infrastructure.[25]

In the Northeast, the Chesapeake region is likely to experience particularly severe local sea level rise due to geologic subsidence,[27] and increased precipitation generally (see Ch. 2: Our Changing Climate, Key Message 5, and Ch.16: Northeast), along with an increased incidence of extreme weather events. The presence of large populations with associated transportation systems in coastal areas increases the potential impacts of sea level rise, storm surge, and precipitation-induced flooding.

The Southeast is subject to the interacting effects of sea level rise, increased precipitation, and other extreme events. The Southeast includes Virginia, so it shares the threat of regional sea level rise in the Chesapeake. In Louisiana, climate change poses a significant threat to transportation infrastructure of national significance.[11]

Midwest transportation infrastructure is subject to changing water levels on the Great Lakes.[54] Barge traffic disruptions, due to flooding or drought on the Mississippi/Missouri/Ohio river system, might be induced by changes in precipitation patterns.

A major concern in the Southwest is that declining precipitation (see Ch. 2: Our Changing Climate, Key Message 5) may induce changes in the economy and society that will affect the transportation systems that serve this region. In the Southwest, rail and highway systems may be exposed to increased heat damage from the higher temperatures. San Francisco Bay, which encompasses two major airports and numerous key transportation links, is at risk for sea level rise and storm surge.[61]

Much of the economy of the Northwest is built around electricity and irrigation from a network of dams. The performance of this system may be affected by changing precipitation patterns, with potential consequences for agriculture and industry, and, consequently for transportation systems. In addition, the Seattle area may be affected by sea level rise.[63]

Many relevant and recent climate data and models predict more intense precipitation events in much of the U.S., especially the Great Plains, Midwest, Northeast, and Southeast, with decreased precipitation in parts of the Southwest and Southeast (see Ch. 2: Our Changing Climate, Key Message 5).

New information and remaining uncertainties

Recent data clearly show – and climate models further substantiate – an increase in the intensity of precipitation events throughout much of the U.S.

There is a need for a better definition of the magnitude of increased storm intensity so that accurate return frequency curves can be established.

New regional climate model data from CMIP5 will have a significant impact on regional impact assessments.

Climate and impact data desired by transportation planners may be different from the projections generated by regional climate models. This presents a number of challenges:

Regional scale transportation impacts are often determined by flood risk and by water flows in rivers and streams. Flooding is, of course, linked to precipitation, but the linkage between precipitation and hydrology is very complex. Precipitation, as projected by climate models, is often difficult to convert into predictions of future flooding, which is what infrastructure designers need.

Similarly, an ice storm would be an extreme event for a transportation planner, but the frequency of ice storms has not yet been derived from climate models. More generally, improved methods of deriving the frequency of infrastructure-affecting weather events from regional climate models may be helpful in assessing climate impacts on transportation systems.

There are uncertainties associated with the correlation between a warming climate and increased hurricane intensity.

In regions likely to see decreased precipitation, especially those areas subject to drought, stronger correlations to fire threat and lowered water levels in major waterways are needed as projections of climate models.

Planning tools and models can present a step-by-step process for connecting the risk of impact with specific planning strategies such as assessing the vulnerability of existing and proposed infrastructure and then identifying key adaptation practices to address the risk.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high** that extreme weather events will affect transportation in all areas of the country.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.

Description of evidence base

The economic cost of climate change to the transportation sector has been little studied. However, there is substantial evidence that costs will be significant. A recent study of climate change in New York indicated that a storm surge severe enough to flood Manhattan tunnels might cost as much as $100 billion.[60] The actual experience of Hurricane Sandy, where multiple tunnels were flooded, attests to the scale of the costs and disruption that attend an event of this magnitude (See also Ch. 11: Urban; Box on Hurricane Sandy). A study of the risk to specific infrastructure elements in Alaska[26] estimated the net present value of the extra cost from climate change at $2 to $4 billion through 2030, and $4 to $8 billion through 2080.

The indirect evidence for significant costs from climate change impacts begin with the consequences of recent hurricanes, particularly on the Eastern seaboard, where Hurricane Irene, a rather minor storm, produced unexpectedly heavy infrastructure damage from heavy rains.[75] The economic cost of infrastructure damage is often greater than the cost of repairing or replacing infrastructure.

In addition, a recent study of on-road congestion estimates the annual cost of highway congestion at about $100 billion,[5] and the Federal Highway Administration estimates that weather accounts for about 15% of total delay.[4] Similarly, a recent study of aviation congestion indicates that the annual cost of airline delay is about $33 billion[3] and that weather accounts for more than a third of airline delays. There is a strong circumstantial case to be made that increased frequency of extreme events (as defined by climate scientists) will produce increased traffic and aviation delays. Given the scale of current costs, even small changes in delay can have substantial economic costs.

There is little published material on transportation adaptation costs and benefits in the literature, in part because "adaptation" is an abstraction (see Ch. 28: Adaptation). Climate change is statistical weather, and manifests itself as a change in the frequency of events that would still occur (but with lower frequency) in the absence of climate change. Transportation agencies decide to protect (or not) specific pieces of infrastructure based on a range of considerations, including age and condition, extent of current and future usage, and cost of protection, as well as changing weather patterns. The authors, however, are aware, that transportation systems have always been required to adapt to changing conditions, and that, in general, it is almost always far less expensive to protect useful infrastructure than to wait for it to collapse. This professional experience, based on examination of multitudes of individual engineering studies, is the basis for the conclusion in this report (for example, Caltrans Climate Change Workshop 2011, CCSP 2008, and Meyer 2008[11,12,69]).

There are numerous examples of actions taken by state and local governments to enhance resilience and reduce climate impact costs on transportation, including land-use planning to discourage development in vulnerable areas, establishment of design guidelines to reduce vulnerability to sea level rise, use of effective stormwater management techniques, and coordinated emergency response systems.[7,69]

New information and remaining uncertainties

There is relatively little information on the costs of climate change in the transportation sector, and less on the benefits of adaptation. Much of the available research is focused on the costs of replacing assets that are affected by extreme weather events, with far less effort devoted to both longer-term impacts of climate change on transportation systems (such as inundation of coastal roads due to sea level rise) and to the broader effects of disrupted facilities on network operations or on the community, for example, rerouting of traffic around bottlenecks or evacuation of sensitive populations from vulnerable areas.

Calculating climate impact and adaptation costs and benefits is an exceptionally complex problem, particularly at high levels of aggregation, since both costs and benefits accrue based on a multitude of location-specific events. In addition, all of the methodological issues that are confronted by any long-term forecasting exercise are present. The forecasting problem may be more manageable at the local and regional scales at which most transportation decisions are usually made.

Assessment of confidence based on evidence

The authors have **high** confidence that climate impacts will be costly to the transportation sector, but are far less confident in assessing the exact magnitude of costs, based on the available evidence and their experience. The authors also have **high** confidence, based upon their experience, that costs may be significantly reduced by adaptation action, though, as noted, the magnitude of such potential reductions on a national scale would be difficult to determine.

Climate Change Impacts in the United States

CHAPTER 6
AGRICULTURE

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On the Web: http://nca2014.globalchange.gov/report/sectors/agriculture

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

6 AGRICULTURE

KEY MESSAGES

1. **Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.**
2. **Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.**
3. **Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.**
4. **The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.**
5. **Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.**
6. **Climate change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts.**

The United States produces nearly $330 billion per year in agricultural commodities, with contributions from livestock accounting for roughly half of that value (Figure 6.1).[1] Production of all commodities will be vulnerable to direct impacts (from changes in crop and livestock development and yield due to changing climate conditions and extreme weather events) and indirect impacts (through increasing pressures from pests and pathogens that will benefit from a changing climate). The agricultural sector continually adapts to climate change through changes in crop rotations, planting times, genetic selection, fertilizer management, pest management, water management, and shifts in areas of crop production. These have proven to be effective strategies to allow previous agricultural production to increase, as evidenced by the continued growth in production and efficiency across the United States.

Climate change poses a major challenge to U.S. agriculture because of the critical dependence of the agricultural system on climate and because of the complex role agriculture plays in rural and national social and economic systems (Figure 6.2). Climate change has the potential to both positively and negatively affect the location, timing, and productivity of crop, livestock, and fishery systems at local, national, and global scales. It will also alter the stability of food supplies and create new food security challenges for the United States as the world seeks to feed nine billion people by 2050. U.S. agriculture exists as part of the global economy and agricultural exports have outpaced imports as part of the overall balance of trade. However, climate change will affect the quantity of produce available for export and import as well as prices (Figure 6.3).

The cumulative impacts of climate change will ultimately depend on changing global market conditions as well as responses to local climate stressors, including farmers adjusting planting patterns in response to altered crop yields and crop species, seed producers investing in drought-tolerant varieties, and nations restricting trade to protect food security. Adaptive actions in the areas of consumption, production, education, and research involve seizing opportunities to avoid economic damages and decline in food quality, minimize threats posed by climate stress, and in some cases increase profitability.

Key Message 1: Increasing Impacts on Agriculture

Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.

Impacts on Crop Production

Producers have many available strategies for adapting to the average temperature and precipitation changes projected (Ch. 2: Our Changing Climate)[2] for the next 25 years. These strategies include continued technological advancements, expansion of irrigated acreage, regional shifts in crop acreage and crop species, other adjustments in inputs and outputs, and changes in livestock management practices in response to changing climate patterns.[3,4] However, crop production projections often fail to consider the indirect impacts from weeds, insects, and diseases that accompany changes in both average trends and extreme events, which can increase losses significantly.[2,5] By mid-century, when temperature increases are projected to be between 1.8°F and 5.4°F and precipitation extremes are further intensified, yields of major U.S. crops and farm profits are expected to decline.[6,7] There have already been detectable impacts on production due to increasing temperatures.[8] Over time, climate change is expected to increase the annual variation in crop and livestock production because of its effects on weather patterns and because of increases in some types of extreme weather events.[9,10] Overall implications for production are for increased uncertainty in production totals, which affects both domestic and international markets and food prices. Recent analysis suggests that climate change has an outsized influence on year-to-year swings in corn prices in the United States.[11]

U.S. Agriculture

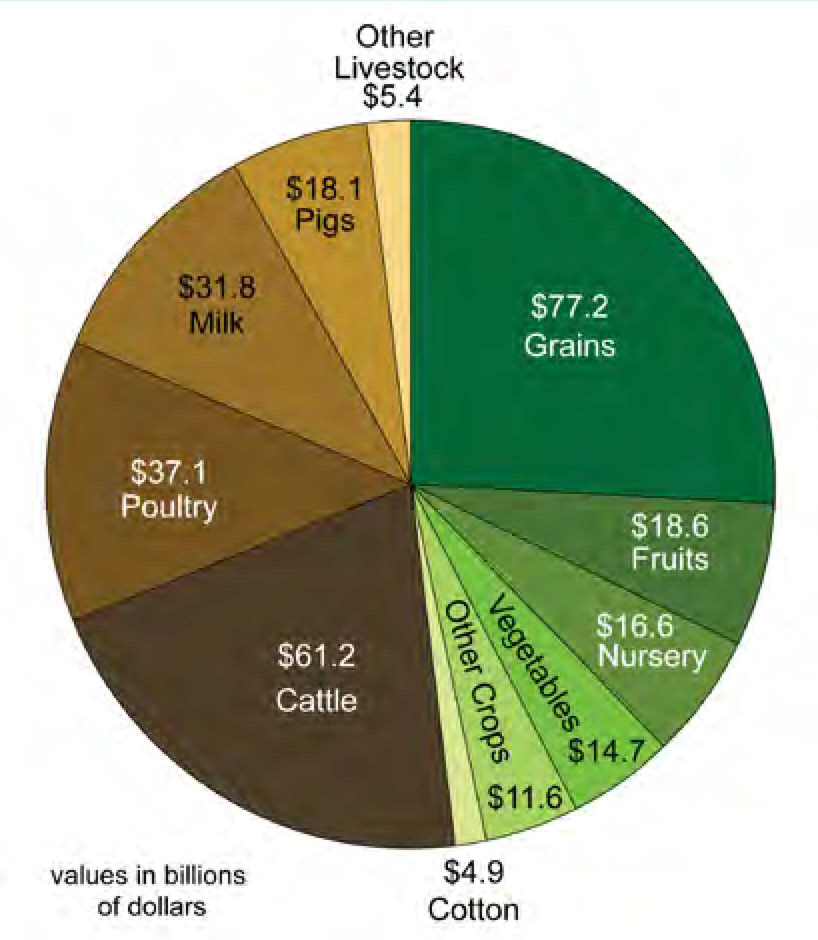

Figure 6.1. U.S. agriculture includes 300 different commodities with a nearly equal division between crop and livestock products. This chart shows a breakdown of the monetary value of U.S. agriculture products by category. (Data from 2007 Census of Agriculture, USDA National Agricultural Statistics Service 2008[12]).

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Agricultural Distribution

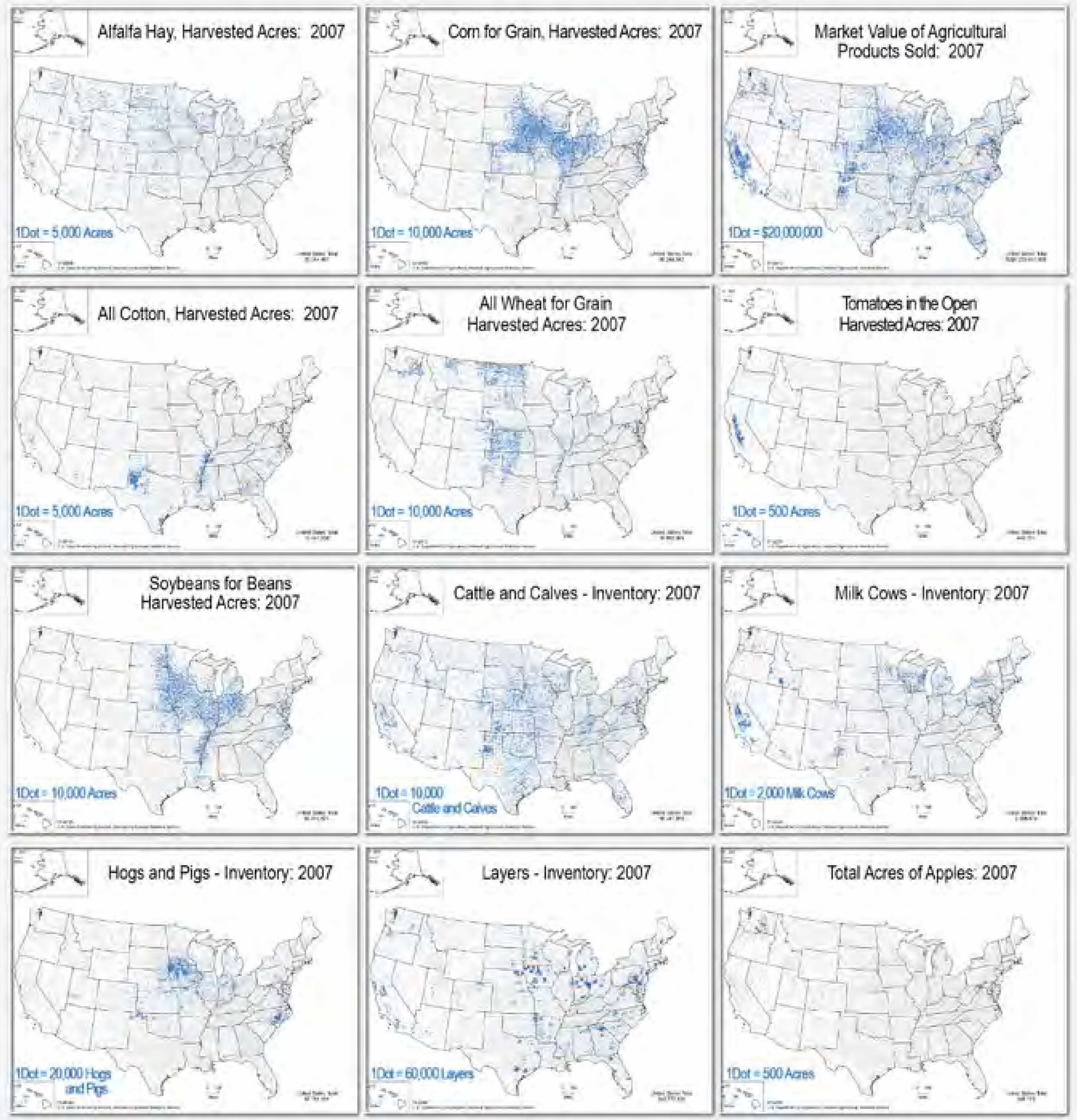

Figure 6.2. Agricultural activity is distributed across the U.S. with market value and crop types varying by region. In 2010, the total market value was nearly $330 billion. Wide variability in climate, commodities, and practices across the U.S. will likely result in differing responses, both in terms of yield and management. (Figure source: USDA National Agricultural Statistics Service 2008[13]).

U.S. Agricultural Trade

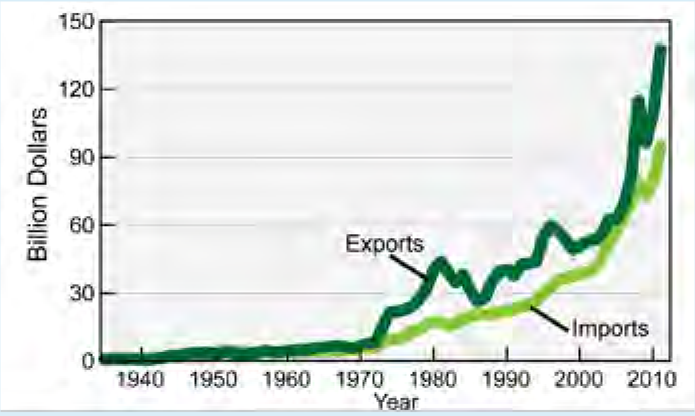

Figure 6.3. U.S. agriculture exists in the context of global markets. Climate is among the important factors that affect these markets. For example, the increase in U.S. food exports in the 1970s is attributed to a combination of rising incomes in other nations, changes in national currency values and farm policies, and poor harvests in many nations in which climate was a factor. Through seasonal weather impacts on harvests and other impacts, climate change will continue to be a factor in global markets. The graph shows U.S. imports and exports for 1935-2011 in adjusted dollar values. (Data from USDA Economic Research Service 2012[14]).

Plant response to climate change is dictated by complex interactions among carbon dioxide (CO_2), temperature, solar radiation, and precipitation. Each crop species has a temperature range for growth, along with an optimum temperature.[9] Plants have specific temperature tolerances, and can only be grown in areas where their temperature thresholds are not exceeded. As temperatures increase over this century, crop production areas may shift to follow the temperature range for optimal growth and yield of grain or fruit. Temperature effects on crop production are only one component; production over years in a given location is more affected by available soil water during the growing season than by temperature, and increased variation in seasonal precipitation, coupled with shifting patterns of precipitation within the season, will create more variation in soil water availability.[9,15] The use of a model to evaluate the effect of changing temperatures in the absence of changes in water availability reveals that crops in California's Central Valley will respond differently to projected temperature increases, as illustrated in Figure 6.4. This example demonstrates one of the methods available for studying the potential effects of climate change on agriculture.

Crop Yield Response to Warming in California's Central Valley

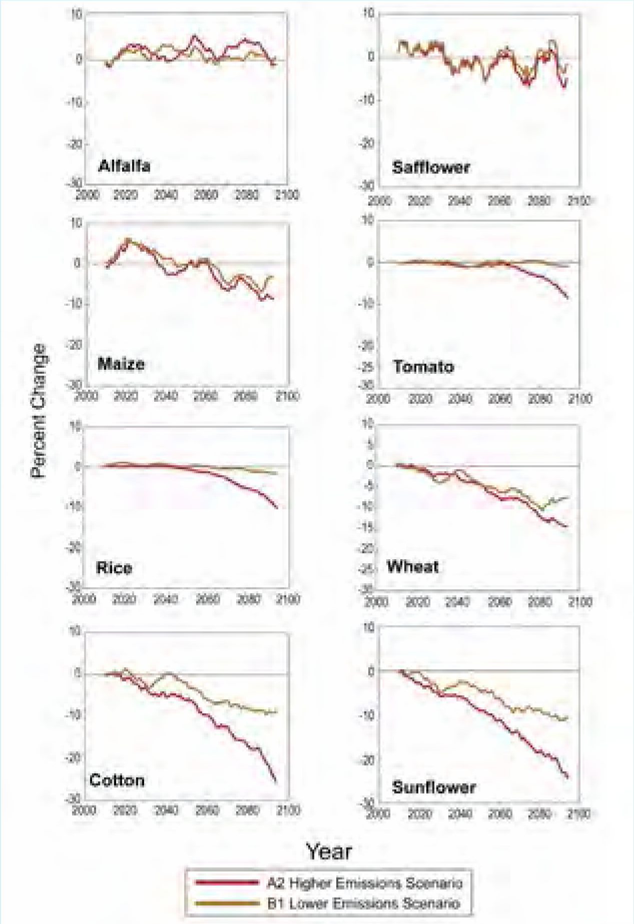

Figure 6.4. Changes in climate through this century will affect crops differently because individual species respond differently to warming. This figure is an example of the potential impacts on different crops within the same geographic region. Crop yield responses for eight crops in the Central Valley of California are projected under two emissions scenarios, one in which heat-trapping gas emissions are substantially reduced (B1) and another in which these emissions continue to grow (A2). This analysis assumes adequate water supplies (soil moisture) and nutrients are maintained while temperatures increase. The lines show five-year moving averages for the period from 2010 to 2094, with the yield changes shown as differences from the year 2009. Yield response varies among crops, with cotton, maize, wheat, and sunflower showing yield declines early in the period. Alfalfa and safflower showed no yield declines during the period. Rice and tomato do not show a yield response until the latter half of the period, with the higher emissions scenario resulting in a larger yield response. (Figure source: adapted from Lee et al. 2011[16]).

One critical period in which temperatures are a major factor is the pollination stage; pollen release is related to development of fruit, grain, or fiber. Exposure to high temperatures during this period can greatly reduce crop yields and increase the risk of total crop failure. Plants exposed to high nighttime temperatures during the grain, fiber, or fruit production period experience lower productivity and reduced quality.[15] These effects have already begun to occur; high nighttime temperatures affected corn yields in 2010 and 2012 across the Corn Belt. With the number of nights with hot temperatures projected to increase as much as 30%, yield reductions will become more prevalent.[9]

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Projected Changes in Key Climate Variables Affecting Agricultural Productivity

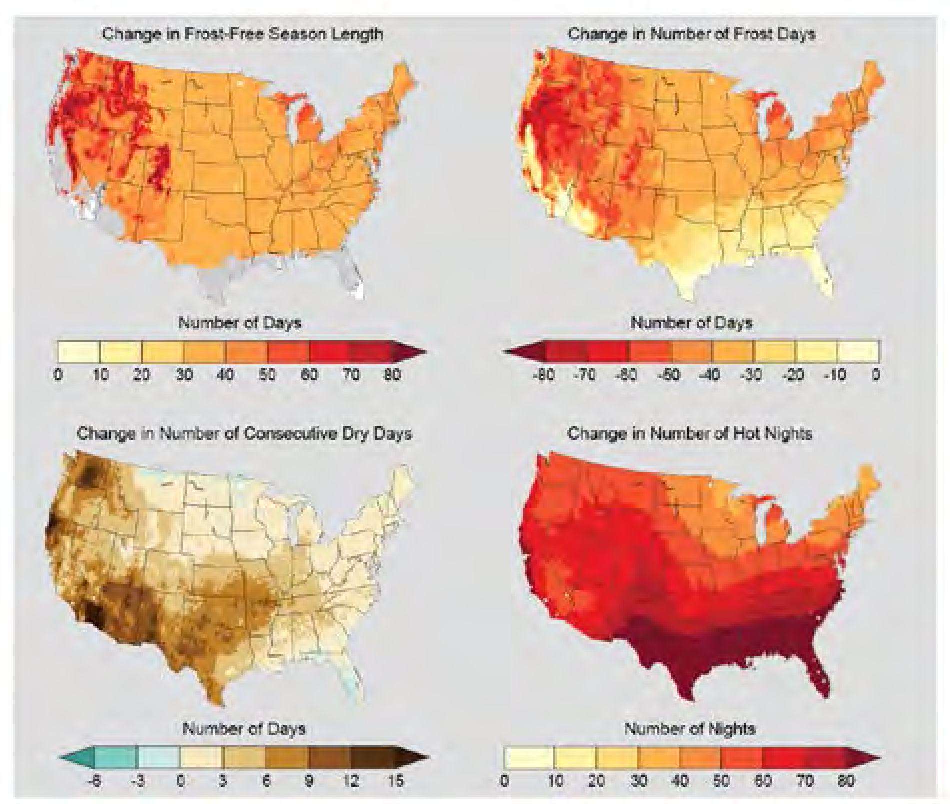


Figure 6.5. Many climate variables affect agriculture. The maps above show projected changes in key climate variables affecting agricultural productivity for the end of the century (2070-2099) compared to 1971-2000. Changes in climate parameters critical to agriculture show lengthening of the frost-free or growing season and reductions in the number of frost days (days with minimum temperatures below freezing), under an emissions scenario that assumes continued increases in heat-trapping gases (A2). Changes in these two variables are not identical, with the length of the growing season increasing across most of the United States and more variation in the change in the number of frost days. Warmer-season crops, such as melons, would grow better in warmer areas, while other crops, such as cereals, would grow more quickly, meaning less time for the grain itself to mature, reducing productivity.[9] Taking advantage of the increasing length of the growing season and changing planting dates could allow planting of more diverse crop rotations, which can be an effective adaptation strategy. On the frost-free map, white areas are projected to experience no freezes for 2070-2099, and gray areas are projected to experience more than 10 frost-free years during the same period. In the lower left graph, consecutive dry days are defined as the annual maximum number of consecutive days with less than 0.01 inches of precipitation. In the lower right graph, hot nights are defined as nights with a minimum temperature higher than 98% of the minimum temperatures between 1971 and 2000. (Figure source: NOAA NCDC / CICS-NC).

Temperature and precipitation changes will include an increase in both the number of consecutive dry days (days with less than 0.01 inches of precipitation) and the number of hot nights (Figure 6.5). The western and southern parts of the nation show the greatest projected increases in consecutive dry days, while the number of hot nights is projected to increase throughout the U.S. These increases in consecutive dry days and hot nights will have negative impacts on crop and animal production. High nighttime temperatures during the grain-filling period (the period between the fertilization of the ovule and the production of a mature seed in a plant) increase the rate of grain-filling and decrease the length of the grain-filling period, resulting in reduced grain yields. Exposure to multiple hot nights increases the degree of stress imposed on animals resulting in reduced rates of meat, milk, and egg production.[17]

Though changes in temperature, CO_2 concentrations, and solar radiation may benefit plant growth rates, this does not equate to increased production. Increasing temperatures cause cultivated plants to grow and mature more quickly. But because the soil may not be able to supply nutrients at required rates for faster growing plants, plants may be smaller, reducing grain, forage, fruit, or fiber production. Reduction in solar radiation in agricultural areas due to increased clouds and humidity in the last 60 years[18] is projected to continue[19] and may partially offset the acceleration of plant growth due to higher temperatures and CO_2 levels, depending on the crop. In vegetables, exposure to temperatures in the range of 1.8°F to 7.2°F above optimal moderately reduces yield, and exposure to temperatures more than 9°F to 12.6°F above optimal often leads to severe if not total production losses. Selective breeding and genetic engineering for both plants and animals provides some opportunity for adapting to climate change; however, development of new varieties in perennial specialty crops commonly requires 15 to 30 years or more, greatly limiting adaptive opportunity, unless varieties could be introduced from other areas. Additionally, perennial crops require time to reach their production potential.

A warmer climate will affect growing conditions, and the lack of cold temperatures may threaten perennial crop production (Figure 6.6). Perennial specialty crops have a winter chilling requirement (typically expressed as hours when temperatures are between 32°F and 50°F) ranging from 200 to 2,000 cumulative hours. Yields decline if the chilling requirement is not completely satisfied, because flower emergence and viability is low.[20] Projections show that chilling requirements for fruit and nut trees in California will not be met by the middle to the end of this century.[21] For most of the Northeast, a 400-hour chilling requirement for apples is projected to continue to be met during this century, but crops with prolonged chilling re-

Reduced Winter Chilling Projected for California

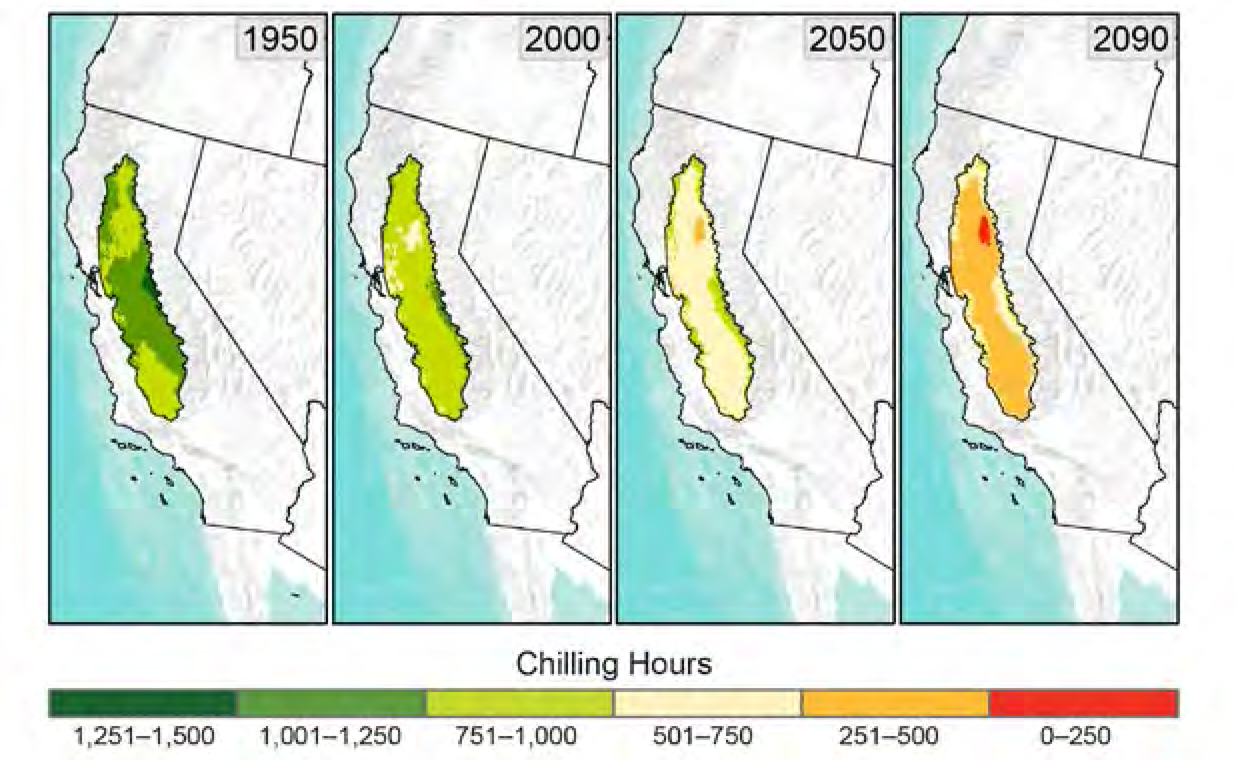


Figure 6.6. Many perennial plants (such as fruit trees and grape vines) require exposure to particular numbers of chilling hours (hours in which the temperatures are between 32°F and 50°F over the winter). This number varies among species, and many trees require chilling hours before flowering and fruit production can occur. With rising temperatures, chilling hours will be reduced. One example of this change is shown here for California's Central Valley, assuming that observed climate trends in that area continue through 2050 and 2090. Under such a scenario, a rapid decrease in the number of chilling hours is projected to occur.

By 2000, the number of chilling hours in some regions was 30% lower than in 1950. Based on the A2 emissions scenario that assumes continued increases in heat-trapping gases relative to 1950, the number of chilling hours is projected to decline by 30% to 60% by 2050 and by up to 80% by 2100. These are very conservative estimates of the reductions in chilling hours because climate models project not just simple continuations of observed trends (as assumed here), but temperature trends rising at an increasing rate.[21] To adapt to these kinds of changes, trees with a lower chilling requirement would have to be planted and reach productive age.

Various trees and grape vines differ in their chilling requirements, with grapes requiring 90 hours, peaches 225, apples 400, and cherries more than 1,000.[21] Increasing temperatures are likely to shift grape production for premium wines to different regions, but with a higher risk of extremely hot conditions that are detrimental to such varieties.[24] The area capable of consistently producing grapes required for the highest-quality wines is projected to decline by more than 50% by late this century.[24] (Figure source: adapted from Luedeling et al. 2009[21]).

quirements, such as plums and cherries (with chilling requirements of more than 700 hours), could be negatively affected, particularly in southern parts of the Northeast.[21,22] Warmer winters can lead to early bud burst or bloom of some perennial plants, resulting in frost damage when cold conditions occur in late spring[15], as was the case with cherries in Michigan in 2012, leading to an economic impact of $220 million (Andresen 2012, personal communication).[23]

The effects of elevated CO_2 on grain and fruit yield and quality are mixed. Some experiments have documented that elevated CO_2 concentrations can increase plant growth while increasing water use efficiency.[25,26] The magnitude of CO_2 growth stimulation in the absence of other stressors has been extensively analyzed for crop and tree species[27,28] and is relatively well understood; however, the interaction with changing temperature, ozone, and water and nutrient constraints creates uncertainty in the magnitude of these responses.[29] In plants such as soybean and alfalfa, elevated CO_2 has been associated with reduced nitrogen and protein content, causing a reduction in grain and forage quality and reducing the ability of pasture and rangeland to support grazing livestock.[30] The growth stimulation effect of increased atmospheric CO_2 concentrations has a disproportionately positive impact on several weed species. This effect will contribute to increased risk of crop loss due to weed pressure.[28,31]

The advantage of increased water-use efficiency due to elevated CO_2 in areas with limited soil water supply may be offset by other impacts from climate change. Rising average temperatures, for instance, will increase crop water demand, increasing the rate of water use by the crop. Rising temperatures coupled with more extreme wet and dry events, or seasonal shifts in precipitation, will affect both crop water demand and plant production.

Impacts on Animal Production from Temperature Extremes

Animal agriculture is a major component of the U.S. agriculture system (Figure 6.1). Changing climatic conditions affect animal agriculture in four primary ways: 1) feed-grain production, availability, and price; 2) pastures and forage crop production and quality; 3) animal health, growth, and reproduction; and 4) disease and pest distributions.[32] The optimal environmental conditions for livestock production include temperatures and other conditions for which animals do not need to significantly alter behavior or physiological functions to maintain relatively constant core body temperature.

Optimum animal core body temperature is often maintained within a 4°F to 5°F range, while deviations from this range can cause animals to become stressed. This can disrupt performance, production, and fertility, limiting the animals' ability to produce meat, milk, or eggs. In many species, deviations in core body temperature in excess of 4°F to 5°F cause significant reductions in productive performance, while deviations of 9°F to 12.6°F often result in death.[33] For cattle that breed during spring and summer, exposure to high temperatures reduces conception rates. Livestock and dairy production are more affected by the number of days of extreme heat than by increases in average temperature.[34] Elevated humidity exacerbates the impact of high temperatures on animal health and performance.

Animals respond to extreme temperature events (hot or cold) by altering their metabolic rates and behavior. Increases in extreme temperature events may become more likely for animals, placing them under conditions where their efficiency in meat, milk, or egg production is affected. Projected increases in extreme heat events (Ch. 2: Our Changing Climate, Key Message 7) will further increase the stress on animals, leading to the potential for greater impacts on production.[34] Meat animals are managed for a high rate of weight gain (high metabolic rate), which increases their potential risk when exposed to high temperature conditions. Exposure to heat stress disrupts metabolic functions in animals and alters their internal temperature when exposure occurs. Exposure to high temperature events can be costly to producers, as was the case in 2011, when heat-related production losses exceeded $1 billion.[35]

Livestock production systems that provide partial or total shelter to reduce thermal environmental challenges can reduce the risk and vulnerability associated with extreme heat. In general, livestock such as poultry and swine are managed in housed systems where airflow can be controlled and housing temperature modified to minimize or buffer against adverse environmental conditions. However, management and energy costs associated with increased temperature regulation will increase for confined production enterprises and may require modification of shelter and increased water use for cooling.

Key Message 2: Weeds, Diseases, and Pests

Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

Weeds, insects, and diseases already have large negative impacts on agricultural production, and climate change has the potential to increase these impacts. Current estimates of losses in global crop production show that weeds cause the largest losses (34%), followed by insects (18%), and diseases (16%).[36] Further increases in temperature and changes in precipitation patterns will induce new conditions that will affect insect populations, incidence of pathogens, and the geographic distribution of insects and diseases.[15,37] Increasing CO_2 boosts weed growth, adding to the potential for increased competition between crops and weeds.[38] Several weed species benefit more than crops from higher temperatures and CO_2 levels.[28,31]

One concern involves the northward spread of invasive weeds like privet and kudzu, which are already present in the southern states.[39] Changing climate and changing trade patterns are likely to increase both the risks posed by, and the sources of, invasive species.[40] Controlling weeds costs the U.S. more than $11 billion a year, with most of that spent on herbicides. Both herbicide use and costs are expected to increase as temperatures and CO_2 levels rise.[41] Also, the most widely used herbicide in the United States, glyphosate (also known as RoundUp™ and other brand names), loses its efficacy on weeds grown at CO_2 levels projected to occur in the coming decades.[42] Higher concentrations of the chemical and more frequent sprayings thus will be needed, increasing economic and environmental costs associated with chemical use.

Climate change effects on land-use patterns have the potential to create interactions among climate, diseases, and crops.[37,43] How climate change affects crop diseases depends upon the effect that a combination of climate changes has on both the host and the pathogen. One example of the complexity of the interactions among climate, host, and pathogen is aflatoxin (*Aspergillus flavus*). Temperature and moisture availability are crucial for the production of this toxin, and both pre-harvest and post-harvest conditions are critical in understanding the impacts of climate change. High temperatures and drought stress increase aflatoxin production and at the same time reduce the growth of host plants. The toxin's impacts are augmented by the presence of insects, creating a potential for climate-toxin-insect-plant interactions that further affect crop production.[44] Earlier spring and warmer winter conditions are also expected to increase the survival and proliferation of disease-causing agents and parasites.

Insects are directly affected by temperature and synchronize their development and reproduction with warm periods and are dormant during cold periods.[45] Higher winter temperatures increase insect populations due to overwinter survival and, coupled with higher summer temperatures, increase reproductive rates and allow for multiple generations each year.[46] An example of this has been observed in the European corn borer (*Ostrinia nubialis)* which produces one generation in the northern Corn Belt and two or more generations in the southern Corn Belt.[47] Changes in the number of reproductive generations coupled with the shift in ranges of insects will alter insect pressure in a given region.

Superimposed on these climate change related impacts on weed and insect proliferation will be ongoing land-use and land-cover changes (Ch. 13: Land Use & Land Cover Change). For example, northward movement of non-migratory butterflies in Europe and changes in the range of insects were associated with land-use patterns and climate change.[48]

Livestock production faces additional climate change related impacts that can affect disease prevalence and range. Regional warming and changes in rainfall distribution have the potential to change the distributions of diseases that are sensitive to temperature and moisture, such as anthrax, blackleg, and hemorrhagic septicemia, and lead to increased incidence of ketosis, mastitis, and lameness in dairy cows.[33,49]

These observations illustrate some of the interactions among climate change, land-use patterns, and insect populations. Weeds, insects, and diseases thus cause a range of direct and indirect effects on plants and animals from climate change, although there are no simple models to predict the potential interactions. Given the economic impact of these pests and the potential implications for food security, research is critical to further understand these dynamics.

Key Message 3: Extreme Precipitation and Soil Erosion

Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.

Several processes act to degrade soils, including erosion, compaction, acidification, salinization, toxification, and net loss of organic matter (Ch. 15: Biogeochemical Cycles). Several of these processes, particularly erosion, will be directly affected by climate change. Rainfall's erosive power is expected to increase as a result of increases in rainfall amount in northern portions of the United States (see Ch. 2: Our Changing Climate), accompanied by further increases in precipitation intensity.[50] Projected increases in rainfall intensity that include more extreme events will increase soil erosion in the absence of conservation practices.[51,52]

Soil and water are essential resources for agricultural production, and both are subject to new conditions as climate changes. Precipitation and temperature affect the *potential* amount of water available, but the *actual* amount of available water also depends on soil type, soil water holding capacity, and the rate at which water filters through the soil (Figure 6.7 and 6.8). Such soil characteristics, however, are sensitive to changing climate conditions; changes in soil carbon content and soil loss will be affected by direct climate effects through changes in soil temperature, soil water availability, and the amount of organic matter input from plants.[53]

It is all about the water!

Soil is a critical component of agricultural systems, and the changing climate affects the amount, distribution, and intensity of precipitation. Soil erosion occurs when the rate of precipitation exceeds the ability of the soil to maintain an adequate infiltration rate. When this occurs, runoff from fields moves water and soil from the field into nearby water bodies.

Figure 6.7

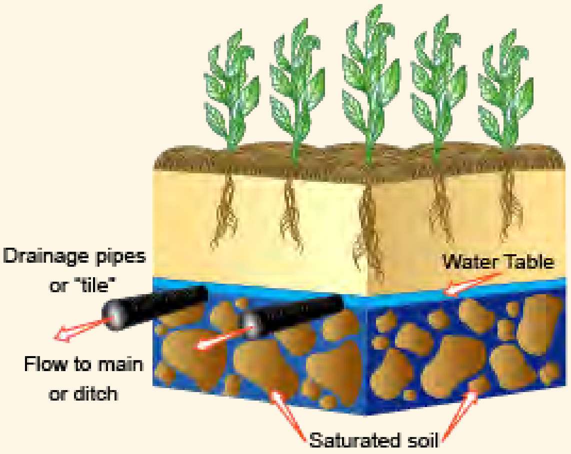
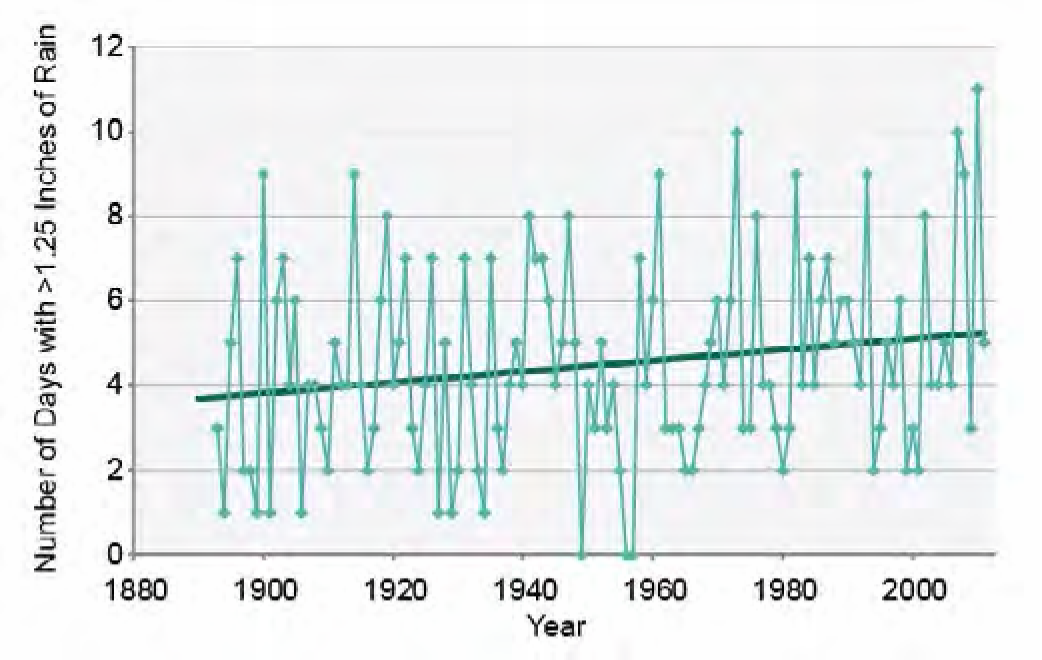


Figure 6.8

Water and soil that are lost from the field are no longer available to support crop growth. The increasing intensity of storms and the shifting of rainfall patterns toward more spring precipitation in the Midwest may lead to more scenes similar to this one (Figure 6.7). An analysis of the rainfall patterns across Iowa has shown there has not been an increase in total annual precipitation; however, there has been a large increase in the number of days with heavy rainfall (Figure 6.9). The increase in spring precipitation is evidenced by a decrease of three days in the number of workable days in the April to May period during 2001 through 2011 in Iowa compared to the period 1980-2000.[15] To offset this increased precipitation, producers have been installing subsurface drainage to remove more water from the fields at a cost of $500 per acre (Figure 6.8). These are elaborate systems designed to move water from the landscape to allow agricultural operations to occur in the spring. Water erosion and runoff is only one portion of the spectrum of extreme precipitation. Wind erosion could increase in areas with persistent drought because of the reduction in vegetative cover. (Photo credit (left): USDA Natural Resources Conservation Service; Figure source (right): NOAA NCDC / CICS-NC).



Increasing Heavy Downpours in Iowa

Figure 6.9. Iowa is the nation's top corn and soybean producing state. These crops are planted in the spring. Heavy rain can delay planting and create problems in obtaining a good stand of plants, both of which can reduce crop productivity. In Iowa soils with even modest slopes, rainfall of more than 1.25 inches in a single day leads to runoff that causes soil erosion and loss of nutrients and, under some circumstances, can lead to flooding. The figure shows the number of days per year during which more than 1.25 inches of rain fell in Des Moines, Iowa. Recent frequent occurrences of such events are consistent with the significant upward trend of heavy precipitation events documented in the Midwest.[51,55] (Figure source: adapted from Takle 2011[56]).

A few of the many important ecosystem services provided by soils include the provision of food, wood, fiber such as cotton, and raw materials; flood mitigation; recycling of wastes; biological control of pests; regulation of carbon and other heat-trapping gases; physical support for roads and buildings; and cultural and aesthetic values.[54] Productive soils are characterized by levels of nutrients necessary for the production of healthy plants, moderately high levels of organic matter, a soil structure with good binding of the primary soil particles, moderate pH levels, thickness sufficient to store adequate water for plants, a healthy microbial community, and the absence of elements or compounds in concentrations that are toxic for plant, animal, and microbial life.

Changes in production practices can have more effect than climate change on soil erosion; however, changes in climate will exacerbate the effects of management practices that do not protect the soil surface from the forces of rainfall. Erosion is managed through maintenance of cover on the soil surface to reduce the effect of rainfall intensity. Studies have shown that a reduction in projected crop biomass (and hence the amount of crop residue that remains on the surface over the winter) will increase soil loss.[57,58] Expected increases in soil erosion under climate change also will lead to increased off-site, non-point-source pollution. Soil conservation practices will therefore be an important element of agricultural adaptation to climate change.[59]

Rising temperatures and CO_2 and shifting precipitation patterns will alter crop-water requirements, crop-water availability, crop productivity, and costs of water access across the agricultural landscape. Higher temperatures are projected to increase both evaporative losses from land and water surfaces and transpiration losses (through plant leaves) from non-crop land cover, potentially reducing annual runoff and streamflow for a given amount of precipitation. The resulting shift in crop health will, in turn, drive changes in cropland allocations and production systems.

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Key Message 4: Heat and Drought Damage

The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.

Climate change projections suggest an increase in extreme heat, severe drought, and heavy precipitation.[60] Extreme climate conditions, such as dry spells, sustained droughts, and heat waves all have large effects on crops and livestock. The timing of extreme events will be critical because they may occur at sensitive stages in the life cycles of agricultural crops or reproductive stages for animals, diseases, and insects. Extreme events at vulnerable times could result in major impacts on growth or productivity, such as hot-temperature extreme weather events on corn during pollination. By the end of this century, the occurrence of very hot nights and the duration of periods lacking agriculturally significant rainfall are projected to increase. Recent studies suggest that increased average temperatures and drier conditions will amplify future drought severity and temperature extremes.[6,61,62] Crops and livestock will be at increased risk of exposure to extreme heat events. Projected increases in the occurrence of extreme heat events will expose production systems to conditions exceeding maximum thresholds for given species more frequently. Goats, sheep, beef cattle, and dairy cattle are the livestock species most widely managed in extensive outdoor facilities. Within physiological limits, animals can adapt to and cope with gradual thermal changes, though shifts in thermoregulation may result in a loss of productivity.[63] Lack of prior conditioning to rapidly changing or adverse weather events, however, often results in catastrophic deaths in domestic livestock and losses of productivity in surviving animals.[34]

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Key Message 5: Rate of Adaptation

Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.

There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies.[64] Much of the economic literature suggests that in the short term, producers will continue to adapt to weather changes and shocks as they always have, with changes in the timing of field operations, shifts in crops grown, and changing tillage or irrigation practices.[64] In the longer term, however, existing adaptive technologies will likely not be sufficient to buffer the impacts of climate change without significant impacts to domestic producers, consumers, or both. New strategies for building long-term resilience include both new technologies and new institutions to facilitate appropriate, informed producer response to a changing climate. Furthermore, there are both public and private costs to adjusting agricultural production and infrastructure in a manner that enables adaptation.[2] Limits to public investment and constraints on private investment could slow the speed of adaptation, yet potential constraints and limits are not well understood or integrated into economic impact assessments. The economic implications of changing biotic pressures on crops and livestock, and on the agricultural system as a whole, are not well understood, either in the short or long term.[15] Adaptation may also be limited by the availability of inputs (such as land or water), changing prices of other inputs with climate change (such as energy and fertilizer), and by the environmental implications of intensifying or expanding agricultural production.

Adaptation strategies currently used by U.S. farmers to cope with weather and climate changes include changing selection of crops, the timing of field operations, and the increasing use of pesticides to control increased pressure from pests. Technological innovation increases the tools available to farmers in some agricultural sectors. Diversifying crop rotations, integrating livestock with crop production systems, improving soil quality, minimizing off-farm flows of nutrients and pesticides, and other practices typically associated with sustainable agriculture also increase the resiliency of the agricultural system to productivity impacts of climate change.[65,66] In the Midwest, there have been shifts in the distribution of crops and land-use change partially related to the increased demand for biofuels[67] (see also Ch. 10: Energy, Water, and Land for more discussion on biofuels). In California's Central Valley, an adaptation plan consisting of integrated changes in crop mix, irrigation methods, fertilization practices, tillage practices, and land management may be an effective approach to managing climate risk.[68] These practices are available to all agricultural regions of the United States as potential adaptation strategies.

Based on projected climate change impacts in some areas of the United States, agricultural systems may have to undergo more transformative changes to remain productive and profitable in the long term.[65] Research and development of sustainable natural resource management strategies inform adaptation options for U.S. agriculture. More transformative adaptive strategies, such as conversion to integrated crop-livestock farming, may reduce environmental impacts, improve profitability and sustainability, and enhance ecological resilience to climate change in U.S. livestock production systems.[69]

There are many possible responses to climate change that will allow agriculture to adapt over the next 25 years; however, potential constraints to adaptation must be recognized and addressed. In addition to regional constraints on the availability of critical basic resources such as land and water, there are potential constraints related to farm financing and credit availability in the U.S. and elsewhere. Research suggests that such constraints may be significant, especially for small family farms with little available capital.[22,64,70] In addition to the technical and financial ability to adapt to changing average conditions, farm resilience to climate change is also a function of financial capacity to withstand increasing variability in production and returns, including catastrophic loss.[71] As climate change intensifies, "climate risk" from more frequent and intense weather events will add to the existing risks commonly managed by producers, such as those related to production, marketing, finances, regulation, and personal health and safety factors.[72] The role of innovative management techniques and government policies as well as research and insurance programs will have a substantial impact on the degree to which the agricultural sector increases climate resilience in the longer term.

Modern agriculture has continually adapted to many changing factors, both within and outside of agricultural systems. As a result, agriculture in the U.S. over the past century has steadily increased productivity and integration into world markets. Although agriculture has a long history of successful adaptation to climate variability, the accelerating pace of climate change and the intensity of projected climate change represent new and unprecedented challenges to the sustainability of U.S. agriculture. In the short term, existing and evolving adaptation strategies will provide substantial adaptive capacity, protecting domestic producers and consumers from many of the impacts of climate change, except possibly the occurrence of protracted extreme events. In the longer term, adaptation will be more difficult and costly because the physiological limits of plant and animal species will be exceeded more frequently, and the productivity of crop and livestock systems will become more variable.

Key Message 6: Food Security

Climate change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts.


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Climate change impacts on agriculture will have consequences for food security both in the U.S. and globally. Food security includes four components: availability, stability, access, and utilization of food.[73] Following this definition, in 2011, 14.9% of U.S. households did not have secure food supplies at some point during the year, with 5.7% of U.S. households experiencing very low food security.[74] Food security is affected by a variety of supply and demand-side pressures, including economic conditions, globalization of markets, safety and quality of food, land-use change, demographic change, and disease and poverty.[75,76]

Within the complex global food system, climate change is expected to affect food security in multiple ways.[77] In addition to altering agricultural yields, projected rising temperatures, changing weather patterns, and increases in frequency of extreme weather events will affect distribution of food- and water-borne diseases as well as food trade and distribution.[78] This means that U.S. food security depends not only on how climate change affects crop yields at the local and national level, but also on how climate change and changes in extreme events affect food processing, storage, transportation, and retailing, through the disruption of transportation as well as the ability of consumers to purchase food. And because about one-fifth of all food consumed in the U.S. is imported, our food supply and security can be significantly affected by climate variations and changes in other parts of the world. The import share has increased over the last two decades, and the U.S. now imports 13% of grains, 20% of vegetables (much higher in winter months), almost 40% of fruit, 85% of fish and shellfish, and almost all tropical products such as coffee, tea, and bananas (Figure 6.3).[79] Climate extremes in regions that supply these products to the U.S. can cause sharp reductions in production and increases in prices.

In an increasingly globalized food system with volatile food prices, climate events abroad may affect food security in the U.S. while climate events in the U.S. may affect food security globally. The globalized food system can buffer the local impacts of weather events on food security, but can also increase the global vulnerability of food security by transmitting price shocks globally.[80]

The connections of U.S. agriculture and food security to global conditions are clearly illustrated by the recent food price spikes in 2008 and 2011 that highlighted the complex connections of climate, land use, demand, and markets. The doubling of the United Nations Food and Agriculture Organization (FAO) food price index over just a few months in 2010 was caused partly by weather conditions in food-exporting countries such as Australia, Russia, and the United States, but was also driven by increased demand for meat and dairy in Asia, increased energy costs and demand for biofuels, and commodity speculation in financial markets.[81]

Adapting food systems to limit the impacts of climate extremes and changes involves strategies to maintain supply and manage demand as well as an understanding of how other regions of the world adapt their food systems in ways that might affect U.S. agricultural competitiveness, imports, and prices. Supplies can be maintained through adaptations such as reducing waste in the food system, making food distribution systems more resilient to climate risks, protecting food quality and safety in higher temperatures, and policies to ensure food access for disadvantaged populations and during extreme events (Ch. 28 Adaptation).[15,75,76,80,81]

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PHOTO CREDITS

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the process was the development of a foundational technical input report (TIR), "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] A public session conducted as part of the Tri-Societies (https://www.acsmeetings.org/home) meeting held in San Antonio, Texas, on Oct. 16-19, 2011, provided input to this report.

The report team engaged in multiple technical discussions via teleconference, which included careful review of the foundational TIR[15] and of approximately 56 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation.[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that climate change has had and will have impacts on crops and livestock is based on numerous studies and is incontrovertible.[6,7,8]

The literature strongly suggests that carbon dioxide, temperature, and precipitation affect livestock and crop production. Plants have an optimal temperature range to which they are adapted, and regional crop growth will be affected by shifts in that region's temperatures relative to each crop's optimal range. Large shifts in temperature can significantly affect seasonal biomass growth, while changes in the timing and intensity of extreme temperature effects are expected to negatively affect crop development during critical windows such as pollination. Crop production will also be affected by changing patterns of seasonal precipitation; extreme precipitation events are expected to occur more frequently and negatively affect production levels. Livestock production is directly affected by extreme temperature as the animal makes metabolic adjustments to cope with heat stress.[15] Further, production costs in confined systems markedly increase when climate regulation is necessary.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83]

There is insufficient understanding of the effects on crop production of rising carbon dioxide, changing temperatures and more variable precipitation patterns.[9] The combined effects on plant water demand and soil water availability will be critical to understanding regional crop response. The role of increasing minimum temperatures on water demand and growth and senescence rates of plants is an important factor. There is insufficient understanding of how prolonged exposure of livestock to high or cold temperatures affects metabolism and reproductive variables.[26] For grazing animals, climate conditions during the growing season are critical in determining feed availability and quality on rangeland and pastureland.[69]

The information base can be enhanced by evaluating crop growth and livestock production models. This evaluation would further the understanding of the interactions of climate variables and the biological system. Better understanding of projected changes in precipitation will narrow uncertainty about future yield reductions.[9,69]

Assessment of confidence based on evidence

There are a range of controlled environment and field studies that provide the evidence for these findings. Confidence in this key message is therefore judged to be **high**.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe the direct effects of climate on the ecological systems within which crop and livestock operations occur. Many weeds respond more strongly to CO_2 than do crops, and it is believed that the range of many diseases and pests (for both crop and livestock) will expand under warming conditions.[28,31,40] Pests may have increased overwinter survival and fit more generations into a single year, which may also facilitate faster evolution of pesticide resistance. Changing patterns of pressure from weeds, other pests, and disease can affect crop and livestock production in ways that may be costly or challenging to address.[9,15]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83]

In addition to extant species already in the U.S., exotic weeds, diseases, and pests have particular significance in that: 1) they can often be invasive (that is, arrive without normal biological/ecological controls) and highly damaging; 2) with increasing international trade, there are numerous high-threat, high-impact species that will arrive on commodities from areas where some species even now are barely known to modern science, but which have the potential to emerge under a changed climate regime to pose significant risk of establishment in the U.S. and economic loss; and 3) can take advantage of "disturbances," where climate variability acts as an additional ecological disturbance. Improved models and observational data related to how many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses will need to be developed.

A key issue is the extent of the interaction between components of the natural biological system (for example, pests) and the economic biological system (for example, crop or animal). For insects, increased populations are a factor; however, their effect on the plant may be dependent upon the phenological stage of the plant when the insect is at specific phenological stages.[15]

To enhance our understanding of these issues will require a concerted effort to begin to quantify the interactions of pests and the economic crop or livestock system and how each system and their interactions are affected by climate.[15]

Assessment of confidence based on evidence

The scientific literature is beginning to emerge; however, there are still some unknowns about the effects of biotic stresses, and there may well be emergent "surprises" resulting from departures from past ecological equilibria. Confidence is therefore judged to be **medium** that many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation."[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Soil erosion is affected by rainfall intensity and there is evidence of increasing intensity in rainfall events even where the annual mean is reduced.[53] Unprotected soil surfaces will have increased erosion and require more intense conservation practices.[58,59] Shifts in seasonality and type of precipitation will affect both timing and impact of water availability for both rainfed and irrigated agriculture. Evidence is strong that in the future there will be more precipitation globally, and that rain events will be more intense, even if separated by longer periods without rain.[6]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83] Both rainfed and irrigated agriculture will increasingly be challenged, based on improved models and observational data related to the effects of increasing precipitation extremes on loss and degradation of critical agricultural soil and water assets.[51,52]

Precipitation shifts are the most difficult to project, and uncertainty in regional projections increases with time into the future.[61] To improve these projections will require enhanced understanding of shifts in timing, intensity, and magnitude of precipitation events. In the northern U.S., more frequent and severe winter and spring storms are projected, while there is a projected reduction in precipitation in the Southwest (see Ch. 2: Our Changing Climate).

Assessment of confidence based on evidence

The precipitation forecasts are the limiting factor in these assessments; the evidence of the impact of precipitation extremes on soil water availability and soil erosion is well established. Confidence in this key message is therefore judged to be **high**.

Key message #4 Traceable Account

The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications[6,61,62] provide evidence that the occurrence of extreme events is increasing, and exposure of plants or animals to temperatures and soil water conditions (drought, water-logging, flood) outside of the biological range for the given species will cause stress and reduce production.[6,61,62] The direct effects of an extreme event will depend upon the timing of the event relative to the growth stage of the biological system.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture, [82] which informed the 2009 National Climate Assessment.[83]

One key area of uncertainty is the timing of extreme events during the phenological stage of the plant or the growth stage of the animal. For example, plants are more sensitive to extreme high temperatures during the pollination stage compared to vegetative growth stages.[9] A parallel example for animals is relatively strong sensitivity to high temperatures during the conception phase.[34] Milk and egg production are also vulnerable to temperature extremes. The effects of extreme combinations of weather variables must be considered, such as elevated humidity in concert with high temperatures.[34]

Other key uncertainties include inadequate precision in simulations of the timing of extreme events relative to short time periods of crop vulnerability, and temperatures close to key thresholds such as freezing.[22] The uncertainty is amplified by the rarity of extreme events; this rarity means there are infrequent opportunities to study the impact of extreme events. In general, a shift of the distribution of temperatures can increase the frequency of threshold exceedance.[15]

The information base can be enhanced by improving the forecast of extreme events, given that the effect of extreme events on plants or animals is known.[3,61]

Assessment of confidence based on evidence

There is **high** confidence in the effects of extreme temperature events on crops and livestock, and the agreement in the literature is good.

Key message #5 Traceable Account

Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.

Description of evidence base

There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies.[64] In the case of crop production, much of the economic literature suggests that in the short term, producers will continue to adapt to weather changes and shocks as they always have, with changes in the timing of field operations, shifts in crops grown, and changing tillage or irrigation practices.[64] In the longer term, however, existing adaptive technologies will likely not be sufficient to buffer the impacts of climate change without significant impacts to domestic producers, consumers, or both.

New strategies for building long-term resilience include both new technologies and new institutions to facilitate appropriate, informed producer response to a changing climate. Furthermore, there are both public and private costs to adjusting agricultural production and infrastructure in a manner that enables adaptation.[2]

New information and remaining uncertainties

Limits to public investment and constraints on private investment could slow the speed of adaptation, yet potential constraints and limits are not well-understood or integrated into economic impact assessments. The economic implications of changing biotic pressures on crops and livestock, and on the agricultural system as a whole, are not well-understood, either in the short or long term.[15] Adaptation may also be limited by availability of inputs (such as land or water), changing prices of other inputs with climate change (such as energy and fertilizer), and by the environmental implications of intensifying or expanding agricultural production.

It is difficult to fully represent the complex interactions of the entire socio-ecological system within which agriculture operates, to assess the relative effectiveness and feasibility of adaptation strategies at various levels. Economic impact assessments require improved understanding of adaptation capacity and agricultural resilience at the system level, including the agri-ecosystem impacts related to diseases and pests. Economic impact assessments also require improved understanding of adaptation opportunities, economic resilience, and constraints to adaptation at the producer level.[2,64] The economic value of ecological services, such as pollination services, is particularly difficult to quantify and incorporate into economic impact efforts.[15]

Assessment of confidence based on evidence

Emerging evidence about adaptation of agricultural systems to changing climate is beginning to be developed. The complex interactions among all of the system components present a limitation to a complete understanding, but do provide a comprehensive framework for the assessment of agricultural responses to climate change. Given the overall and remaining uncertainty, there is **medium** confidence in this message.

KEY MESSAGE #6 TRACEABLE ACCOUNT

Climate change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts.

Description of evidence base

The relationships among agricultural productivity, climate change, and food security have been documented through ongoing investigations by the Food and Agriculture Organization,[81,84] as well as the U.S. Department of Agriculture,[85] and the National Research Council.[77] There are many factors that affect food security, and agricultural yields are only one of them. Climate change is also expected to affect distribution of food- and waterborne diseases, and food trade and distribution.[78]

New information and remaining uncertainties

The components of food security derive from the intersection of political, physical, economic, and social factors. In many ways the impact of climate change on crop yields is the least complex of the factors that affect the four components of food security (availability, stability, access, and utilization). As the globalized food system is subject to conflicting pressures across scales, one approach to reducing risk is a "cross-scale problem-driven" approach to food security.[76] This and other approaches to understanding and responding to the complexities of the global food system need additional research. Climate change will have a direct impact on crop and livestock production by increasing the variability in production levels from year to year, with varying effects across different regions. Climate change will also affect the distribution of food supplies as a result of disruptions in transportation routes. Addressing food security will require integration of multiple factors, including the direct and indirect impacts of climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainty, there is **high** confidence that climate change impacts will have consequences for food security both in the U.S. and globally through changes in crop yields and food prices, and **very high** confidence that other related factors, including food processing, storage, transportation, and retailing will also be affected by climate change. There is **high** confidence that adaptation measures will help delay and reduce some of these impacts.

Climate Change Impacts in the United States

CHAPTER 7
FORESTS

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On the Web: http://nca2014.globalchange.gov/report/sectors/forests

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

7 FORESTS

KEY MESSAGES

1. **Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.**
2. **U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.**
3. **Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.**
4. **Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.**

Forests occur within urban areas, at the interface between urban and rural areas (wildland-urban interface), and in rural areas. Urban forests contribute to clean air, cooling buildings, aesthetics, and recreation in parks. Development in the wildland-urban interface is increasing because of the appeal of owning homes near or in the woods. In rural areas, market factors drive land uses among commercial forestry and land uses such as agriculture. Across this spectrum, forests provide recreational opportunities, cultural resources, and social values such as aesthetics.[1]

Economic factors have historically influenced both the overall area and use of private forestland. Private entities (such as corporations, family forest owners, and tribes) own 56% of the forestlands in the United States. The remaining 44% of forests are on public lands: federal (33%), state (9%), and county and municipal government (2%).[2] Market factors can influence management objectives for public lands, but societal values also influence objectives by identifying benefits such as environmental services not ordinarily provided through markets, like watershed protection and wildlife habitat. Different challenges and opportunities exist for public and for private forest management decisions, especially when climate-related issues are considered on a national scale. For example, public forests typically carry higher levels of forest biomass, are more remote, and tend not to be as intensively managed as private forestlands.[1]

Forests provide opportunities to reduce future climate change by capturing and storing carbon, as well as by providing resources for bioenergy production (the use of forest-derived plant-based materials for energy production). The total amount of carbon stored in U.S. forest ecosystems and wood products (such as lumber and pulpwood) equals roughly 25 years of U.S. heat-trapping gas emissions at current rates of emission, providing an important national "sink" that could grow or shrink depending on the extent of climate change, forest management practices, policy decisions, and other factors.[3,4] For example, in 2011, U.S. forest ecosystems and the associated wood products industry captured and stored roughly 16% of all carbon dioxide emitted by fossil fuel burning in the United States.[3]

Management choices for public, private, and tribal forests all involve similar issues. For example, increases in wildfire, disease, drought, and extreme events are projected for some regions (see also Ch. 16: Northeast; Ch. 20: Southwest; Ch. 21: Northwest, Key Message 3; and Ch. 22: Alaska). At the same time, there is growing awareness that forests may play an expanded role in carbon management. Urban expansion fragments forests and may limit forest management options. Addressing climate change effects on forestlands requires considering the interactions among land-use practices, energy options, and climate change.[5]

Key Message 1: Increasing Forest Disturbances

Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.

Insect and pathogen outbreaks, invasive species, wildfires, and extreme events such as droughts, high winds, ice storms, hurricanes, and landslides induced by storms[8] are all disturbances that affect U.S. forests and their management (Figure 7.1). These disturbances are part of forest dynamics, are often interrelated, and can be amplified by underlying trends – for example, decades of rising average temperatures can increase damage to forests when a drought occurs.[9] Disturbances that affect large portions of forest ecosystems occur relatively infrequently and in response to climate extremes. Changes in climate in the absence of extreme climate events (and the forest disturbances they trigger) may result in increased forest productivity, but extreme climate events can potentially overturn such patterns.[10]

Factors affecting tree death – such as drought, physiological water stress, higher temperatures, and/or pests and pathogens – are often interrelated, which means that isolating a single cause of mortality is rare.[11,12,13] However, in western forests there have been recent large-scale die-off events due to one or more of these factors,[14,15,16] and rates of tree mortality are well correlated with both rising temperatures and associated increases in evaporative water demand.[17] In eastern forests, tree mortality at large spatial scales was more sensitive

Forest Ecosystem Disturbances

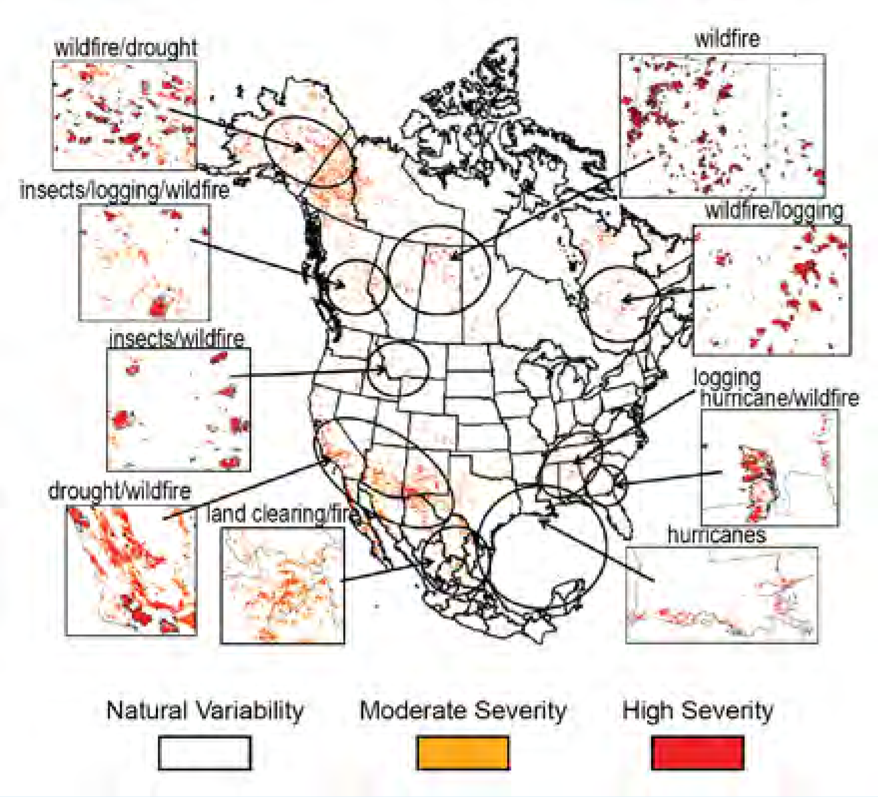

Figure 7.1. An example of the variability and distribution of major ecosystem disturbance types in North America, compiled from 2005 to 2009. Forest disturbance varies by topography, vegetation, weather patterns, climate gradients, and proximity to human settlement. Severity is mapped as a percent change in a satellite-derived Disturbance Index. White areas represent natural annual variability, orange represents moderate severity, and red represents high severity.[6] Fire dominates much of the western forest ecosystems, and storms affect the Gulf Coast. Insect damage is widespread but currently concentrated in western regions, and timber harvest is predominant in the Southeast. (Figure source: modified from Goetz et al. 2012;[7] Copyright 2012 American Geophysical Union).


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A Montana saw mill owner inspects a lodgepole pine covered in pitch tubes that show the tree trying, unsuccessfully, to defend itself against the bark beetle. The bark beetle is killing lodgepole pines throughout the western U.S.


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Warmer winters allow more insects to survive the cold season, and a longer summer allows some insects to complete two life cycles in a year instead of one. Drought stress reduces trees' ability to defend against boring insects. Above, beetle-killed trees in Rocky Mountain National Park in Colorado.

to forest structure (age, tree size, and species composition) and air pollutants than climate over recent decades. Nonetheless, mortality of some eastern tree groups is related to rising temperature[18] and is expected to increase as climate warms.[19]

Future disturbance rates in forests will depend on changes in the frequency of extreme events as well as the underlying changes in average climate conditions.[9,20] Of particular concern is the potential for increased forest disturbance as the result of drought accompanied with warmer temperatures, which can cause both wildfire and tree death. Temperatures have generally been increasing and are projected to increase in the future (see Ch. 2: Our Changing Climate). Therefore, although it is difficult to predict trends in future extreme events,[21] there is a high degree of confidence that future droughts will be accompanied by generally warmer conditions. Trees die faster when drought is accompanied by higher temperatures, so short droughts can trigger mortality if temperatures are higher.[22] Short droughts occur more frequently than long droughts. Consequently, a direct effect of rising temperatures may be substantially greater tree mortality even with no change in drought frequency.[22]

Given strong relationships between climate and fire, even when modified by land use and management, such as fuel treatments (Figure 7.2), projected climate changes suggest that western forests in the United States will be increasingly affected by large and intense fires that occur more frequently.[16,23,24,25] These impacts are compounded by a legacy of fire suppression that has resulted in many U.S. forests becoming increasingly dense.[26] Eastern forests are less likely to experience immediate increases in wildfire, unless a point is reached at which rising temperatures combine with seasonal dry periods, more protracted drought, and/or insect outbreaks to trigger wildfires – conditions that have been seen in Florida (see Ch. 17: Southeast).

Rising temperatures and CO_2 levels can increase growth or alter migration of some tree species;[1,27] however, the relationship between rising temperature and mortality is complex. For example, most functional groups show a decrease in mortality with higher summer temperatures (with the exception of northern groups), whereas warmer winters are correlated with higher mortality for some functional groups.[18] Tree mortality is often the result of a combination of many factors; thus increases in pollutants, droughts, and wildfires will increase the probability of a tree dying (Figure 7.3). Under projected climate conditions, rising temperatures could work together with forest stand characteristics and these other stressors to increase mortality. Recent die-offs have been more severe than projected.[11,14] As temperatures increase to levels projected for mid-century and beyond, eastern forests may be at risk of die-off.[19] New evidence indicates that most tree species can endure only limited abnormal water stress, reinforcing the idea that trees in wetter as well as semiarid forests are vulnerable to drought-induced mortality under warming climates.[28]

Effectiveness of Forest Management in Reducing Wildfire Risk

Figure 7.2. Forest management that selectively removes trees to reduce fire risk, among other objectives (a practice referred to as “fuel treatments”), can maintain uneven-aged forest structure and create small openings in the forest. Under some conditions, this practice can help prevent large wildfires from spreading. Photo shows the effectiveness of fuel treatments in Arizona’s 2002 Rodeo-Chediski fire, which burned more than 400 square miles – at the time the worst fire in state history. Unburned area (left) had been managed with a treatment that removed commercial timber, thinned non-commercial-sized trees, and followed with prescribed fire in 1999. The right side of the photo shows burned area on the untreated slope below Limestone Ridge. (Photo credit: Jim Youtz, U.S. Forest Service).

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Climate change is contributing to increases in wildfires across the western U.S. and Alaska.

Forest Vulnerability to Changing Climate

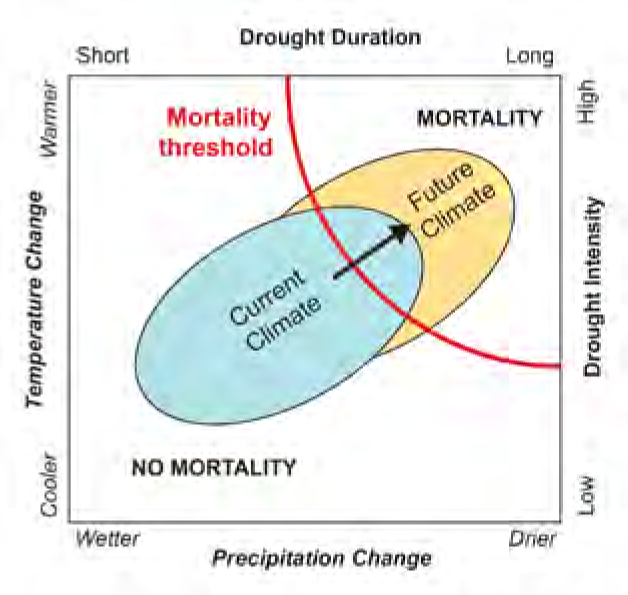

Figure 7.3. The figure shows a conceptual climate envelope analysis of forest vulnerability under current and projected future ranges of variability in climate parameters (temperature and precipitation, or alternatively drought duration and intensity). Climate models project increasing temperatures across the U.S. in coming decades, but a range of increasing or decreasing precipitation depending on region. Episodic droughts (where evaporation far exceeds precipitation) are also expected to increase in duration and/or intensity (see Ch. 2: Our Changing Climate). The overall result will be increased vulnerability of forests to periodic widespread regional mortality events resulting from trees exceeding their physiological stress thresholds.[11] (Figure source: Allen et al. 2010[11]).

Large-scale die-off and wildfire disturbance events could have potential impacts occurring at local and regional scales for timber production, flooding and erosion risks, other changes in water budgets, biogeochemical changes including carbon storage, and aesthetics.[29,30,31] Rising disturbance rates can increase harvested wood output and potentially lower prices; however, higher disturbance rates could make future forest investments more risky (Figure 7.4). Western forests could also lose substantial amounts of carbon storage capacity. For example, an increase in wildfires, insect outbreaks, and droughts that are severe enough to alter soil moisture and nutrient contents can result in changes in tree density or species composition.[10]

Key Message 2: Changing Carbon Uptake

U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.

Climate-related Effects on Trees and Forest Productivity

Forests within the United States grow across a wide range of latitudes and altitudes and occupy all but the driest regions. Current forest cover has been shaped by climate, soils, topography, disturbance frequency, and human activity. Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth is limited by low temperatures and short growing seasons that are gradually being altered by climate change (for species shifts, see Ch. 8: Ecosystems).[32] Forest carbon storage appears to be increasing both globally and within the United States.[33] Continental-scale satellite measurements document a lengthening growing season in the last thirty years, yet earlier spring growth may be negated by mid-summer drought.[34]

By the end of the century, snowmelt may occur a month earlier, but forest drought stress could increase by two months in the Rocky Mountain forests.[35] In the eastern United States, elevated CO_2 and temperature may increase forest growth and potentially carbon storage if sufficient water is available.[1,31,36] Despite recent increases in forest growth, future net forest carbon storage is expected to decline due to accelerating mortality and disturbance.

Forests can be a Source – or a Sink – for Carbon

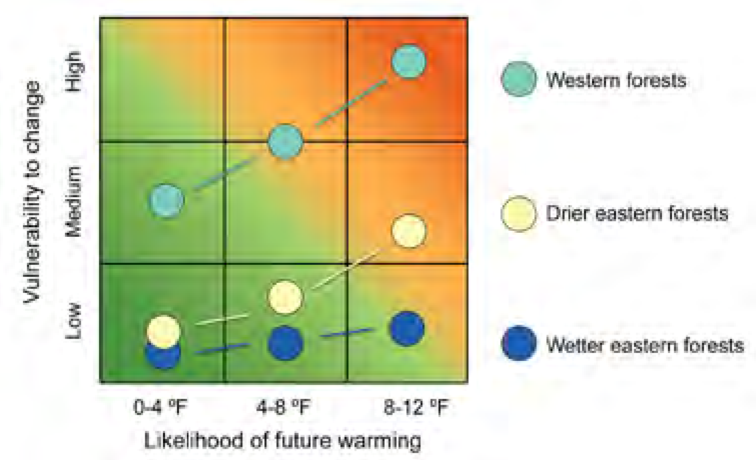

Figure 7.4. Relative vulnerability of different forest regions to climate change is illustrated in this conceptual risk analysis diagram. Forest carbon exchange is the difference between carbon captured in photosynthesis and carbon released by respiration of vegetation and soils. Both photosynthesis and respiration are generally accelerated by higher temperatures, and slowed by water deficits, but the relative strengths of these controls are highly variable. Western forests are inherently limited by evaporation that exceeds precipitation during much of the growing season. Xeric (drier) eastern forests grow on shallow, coarse textured soils and experience water deficits during long periods without rain. Mesic (wetter) eastern forests experience severe water deficits only for relatively brief periods in abnormally dry years so the carbon exchanges are more controlled by temperature fluctuations. (Figure source: adapted from Vose et al. 2012[1]).

Forest Carbon Sequestration and Carbon Management

From the onset of European settlement to the start of the last century, changes in U.S. forest cover due to expansion of agriculture, tree harvests, and settlements resulted in net emissions of carbon.[37,38] More recently, with forests reoccupying land previously used for agriculture, technological advances in harvesting, and changes in forest management, U.S. forests and associated wood products now serve as a substantial carbon sink, capturing and storing more than 227.6 million tons of carbon per year.[3] The amount of carbon taken up by U.S. land is dominated by forests (Figure 7.5), which have annually absorbed 7% to 24% of fossil fuel carbon dioxide (CO_2) emissions in the U.S. over the past two decades. The best estimate is that forests and wood products stored about 16% (833 teragrams, or 918.2 million short tons, of CO_2 equivalent in 2011) of all the CO_2 emitted annually by fossil fuel burning in the United States (see also “Estimating the U.S. Carbon Sink” in Ch. 15: Biogeochemical Cycles).[3]

Forest Growth Provides an Important Carbon Sink

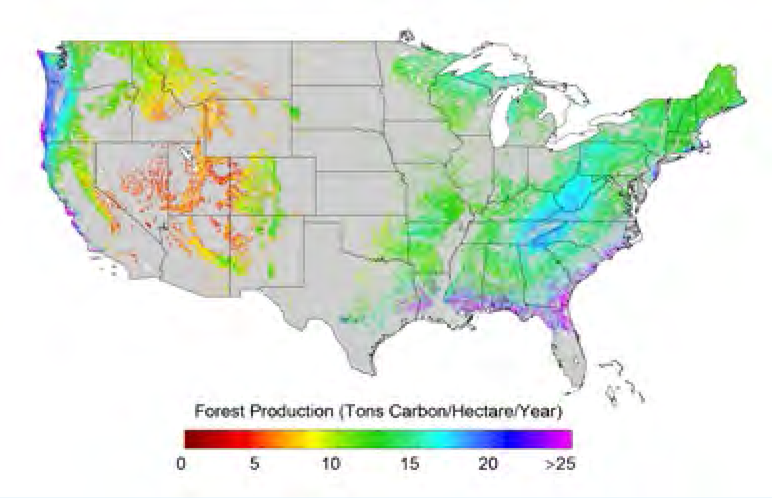

Figure 7.5. Forests are the largest component of the U.S. carbon sink, but growth rates of forests vary widely across the country. Well-watered forests of the Pacific Coast and Southeast absorb considerably more than the arid southwestern forests or the colder northeastern forests. Climate change and disturbance rates, combined with current societal trends regarding land use and forest management, are projected to reduce forest CO_2 uptake in the coming decades.[1] Figure shows average forest growth as measured by net primary production from 2000 to 2006. (Figure source: adapted from Running et al. 2004[46]).

The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (see Figures 7.3 and 7.4), as well as shifts in tree species, ranges, and productivity (Figure 7.6).[19,38] Economic factors will affect any future carbon cycle of forests, as the age class and condition of forests are affected by the acceleration of harvesting,[39,40] land-use changes such as urbanization,[41] changes in forest types,[42] and bioenergy development.[41,43,44,45]

Efforts in forestry to reduce atmospheric CO_2 levels have focused on forest management and forest product use. Forest management strategies include land-use change to increase forest area (afforestation) and/or to avoid deforestation and optimizing carbon management in existing forests. Forest product-use strategies include the use of wood wherever possible as a structural substitute for steel and concrete, which require more carbon emissions to produce.[38] The carbon emissions offset from using wood rather than alternate materials for a range of applications can be two or more times the carbon content of the product.[47]

In the U.S., afforestation (active establishment or planting of forests) has the potential to capture and store a maximum of 225 million tons of additional carbon per year from 2010 to 2110[39,48] (an amount almost equivalent to the current annual carbon storage in forests). Tree and shrub encroachment into grasslands, rangelands, and savannas provides a large potential carbon sink that could exceed half of what existing U.S. forests capture and store annually.[48]

Expansion of urban and suburban areas is responsible for much of the current and expected loss of U.S. forestland, although these human-dominated areas often have extensive tree cover and potential carbon storage (see also Ch. 13: Land Use & Land Cover Change).[41] In addition, the increasing prevalence of extreme conditions that encourage wildfires can convert some forests to shrublands and meadows[25] or permanently reduce the amount of carbon stored in existing forests if fires occur more frequently.[49]

Carbon management on existing forests can include practices that increase forest growth, such as fertilization, irrigation, switching to fast-growing planting stock, shorter rotations, and weed, disease, and insect control.[50] In addition, forest management can increase average forest carbon stocks by increasing the interval between harvests, by decreasing harvest intensity, or by focused density/species management.[4,51] Since 1990, CO_2 emissions from wildland forest fires in the lower 48 United States have averaged about 67 million tons of carbon per year.[52,53] While forest management practices can reduce on-site carbon stocks, they may also help reduce future climate change by providing feedstock material for bioenergy production and by possibly avoiding future, potentially larger, wildfire emissions through fuel treatments (Figure 7.2).[1]

Forests and Carbon

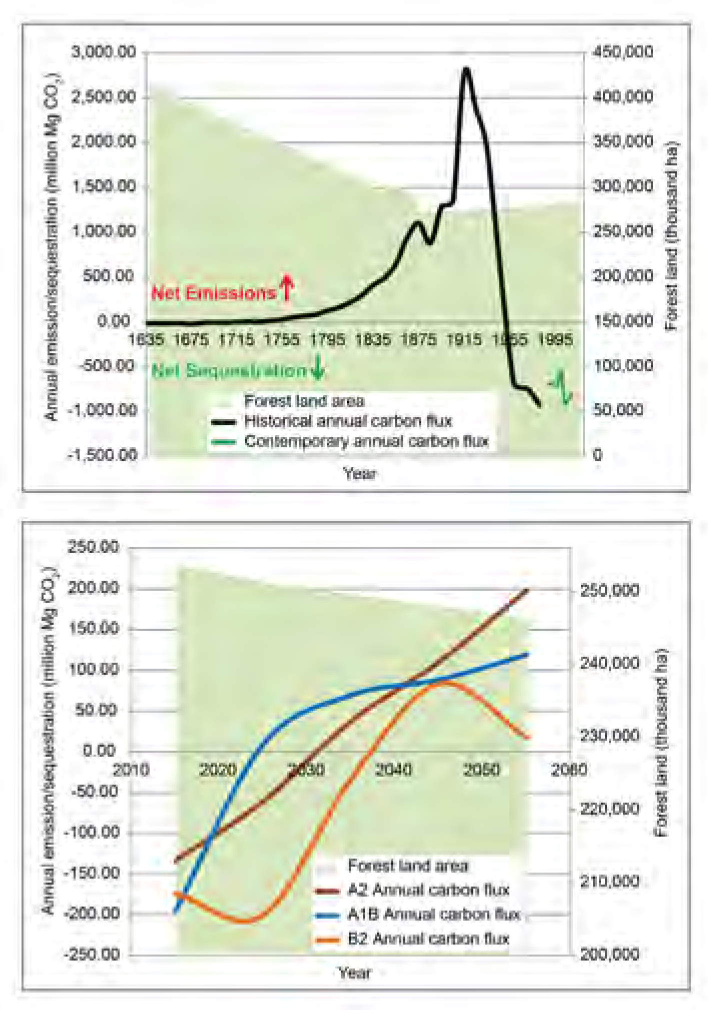

Figure 7.6. Historical, current, and projected annual rates of forest ecosystem and harvested wood product CO_2 net emissions/sequestration in the U.S. from 1635 to 2055. In the top panel, the change in the historical annual carbon emissions (black line) in the early 1900s corresponds to the peak in the transformation of large parts of the U.S. from forested land to agricultural land uses. Green shading shows this decline in forest land area. In the bottom panel, future projections shown under higher (A2) and lower (B2 and A1B) emissions scenarios show forests as carbon sources (due to loss of forest area and accelerating disturbance rates) rather than sinks in the latter half of this century. The A1B scenario assumes similar emissions to the A2 scenario used in this report through 2050, and a slow decline thereafter. (Data from Birdsey 2006;[37] USFS 2012;[41] EPA 2013.[53])

Key Message 3: Bioenergy Potential

Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.

Bioenergy refers to the use of plant-based material to produce energy, and comprises about 28% of the U.S. renewable energy supply (Ch. 10: Energy, Water, and Land). Forest resources potentially could produce bioenergy from 504 million acres of timberland and 91 million acres of other forested land (Figure 7.7). Bioenergy from all sources, including agricultural and forests, could theoretically supply the equivalent of up to 30% of current U.S. petroleum consumption, but only if all relevant policies were optimized.[45] The *maximum* projected potential for forest bioenergy ranges from 3% to 5% of total current U.S. energy consumption.[54]

Forest biomass energy could be one component of an overall bioenergy strategy to reduce emissions of carbon from fossil fuels,[55] while also improving water quality[56,57] and maintaining lands for timber production as an alternative to other socioeconomic options. Active biomass energy markets using wood and forest residues have emerged in the southern and northeastern United States, particularly in states that have adopted renewable fuel standards. The economic viability of using forests for bioenergy depends on regional context and circumstances, such as species type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution, and use.[58] The environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.

The potential for biomass energy to increase timber harvests has led to debates about whether forest biomass energy leads to higher carbon emissions.[44,59] The debate on biogenic emissions regulations revolves around how to account for emissions related to biomass production and use.[60] The forest carbon balance naturally changes over time and also depends on forest management scenarios. For example, utilizing natural beetle-killed forests will yield a different carbon balance than growing and harvesting a live, fast-growing plantation.

Location of Potential Forestry Biomass Resources

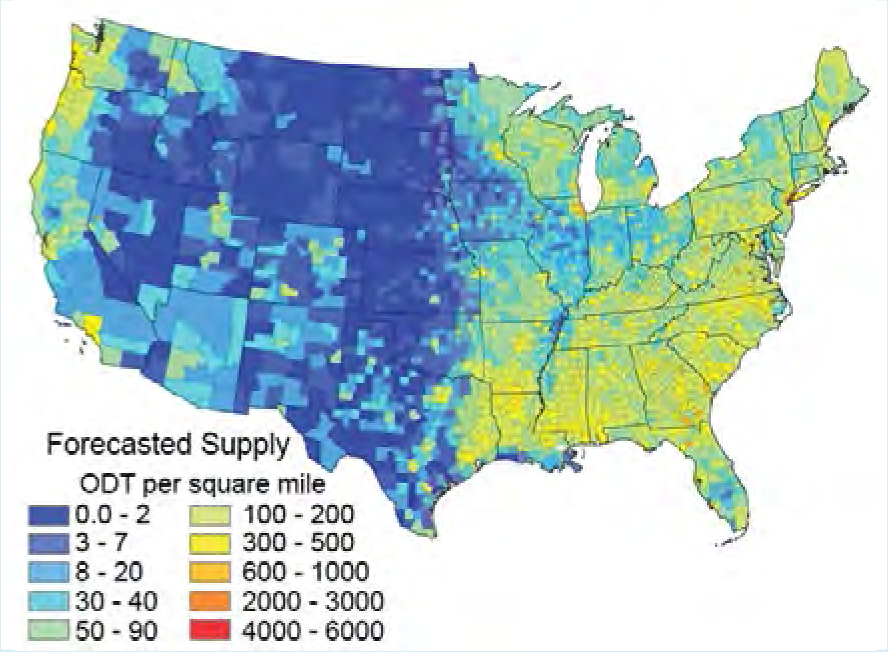

Figure 7.7. Potential forestry bioenergy resources by 2030 at $80 per dry ton of biomass based on current forest area, production rates based on aggressive management for fast-growth, and short rotation bioenergy plantations. Units are oven dry tons (ODT) per square mile at the county level, where an ODT is 2,000 pounds of biomass from which the moisture has been removed. Includes extensive material from existing forestland, such as residues, simulated thinnings, and some pulpwood for bioenergy, among other sources. (Figure source: adapted from U.S. Department of Energy 2011[45]).

Markets for energy from biomass appear to be ready to grow in response to energy pricing, policy, and demand,[44] although recent increases in the supply of natural gas have reduced the perceived urgency for new biomass projects. Further, because energy facilities typically buy the lowest quality wood at prices that rarely pay much more than cutting and hauling costs, they often require a viable saw timber market nearby to ensure an adequate, low-cost supply of material.[61] Where it is desirable to remove dead wood after disturbances to thin forests or to dispose of residues, a viable bioenergy industry could finance such activities. However, the bioenergy market has yet to be made a profitable enterprise in most U.S. regions.

Key Message 4: Influences on Management Choices

Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.

Climate change will affect trees and forests in urban areas, the wildland-urban interface, and in rural areas. It will also challenge forest landowners managing forests for commercial products, energy development, environmental services such as watershed protection, or the conversion of forestland to developed and urban uses or agriculture. With increases in urbanization, the value of forests in and around urban areas in providing environmental services required by urban residents will increase.[41] Potentially the greatest shifts in goods and environmental services produced from forests could occur in rural areas where social and economic factors will interact with the effects of climate change at landscape scales.

Owner objectives, markets for forest products, crops and energy, the monetary value of private land, and policies governing private and public forestland all influence the actions taken to manage U.S. forestlands (56% privately owned, 44% public) (Figure 7.8). Ownership changes can bring changes in forest objectives. Among corporate owners (18% of all forestland), ownership has shifted from forest industry to investment management organizations that may or may not have active forest management as a primary objective. Non-corporate private owners, an aging demographic, manage 38% of forestland. Their primary objectives are maintaining aesthetics and the privacy that the land provides as well as preserving the land as part of their family legacy.[62]

A significant economic factor facing private forest owners is the value of their forestlands for conversion to urban or developed uses. Economic opportunities from forests include wood products, non-timber forest products, recreation activities, and in some cases, environmental services.[1,41] Less than 1% of the volume of commercial trees from U.S. forestlands is harvested annually, and 92% of this harvest comes from private forestlands.[2] Markets for wood products in the United States have been affected by increasingly competitive global markets,[63] and timber prices are not projected to increase without substantial increases in wood energy consumption or other new timber demands.[41] Urban conversions of forestland over the next 50 years could result in the loss of 16 to 31 million acres.[41] The willingness of private forest owners to actively manage forests in the face of climate change will be affected primarily by market and policy incentives, not climate change itself.

The ability of public, private, and tribal forest managers to adapt to future climate change will be enhanced by their capacity to alter management regimes relatively rapidly in the face of changing conditions. The response to climate change may be greater on private forestlands where, in the past, owners have been highly responsive to market and policy signals.[64] These landowners may be able to use existing or current forest management practices to reduce disturbance effects, increase the capture and storage of carbon, and modify plant species distributions under climate change. In addition, policy incentives, such as carbon pricing or cap and trade markets, could influence landowner choices. For human communities dependent upon forest resources, maintaining or enhancing their current resilience to change will influence their ability to respond to future stresses from climate change.[65]

On public, private, and tribal lands, management practices that can be used to reduce disturbance effects include altering tree planting and harvest strategies through species selection and timing; factoring in genetic variation; managing for reduced stand densities, which could reduce wildfire risk; reducing other stressors such as poor air quality; using forest management practices to minimize drought stress; and developing regional networks to mitigate impacts on ecosystem goods and services.[1,30,66] Legally binding regulatory requirements may constrain adaptive management where plants, animals, ecosystems, and people are responding to climate change.[67]

Lack of fine-scale information about the possible effects of climate changes on locally managed forests limits the ability of managers to weigh these risks to their forests against the economic risks of implementing forest management practices such as adaptation and/or mitigation treatments. This knowledge gap will impede the implementation of effective management on public or private forestland in the face of climate change.

Public and Private Forestlands

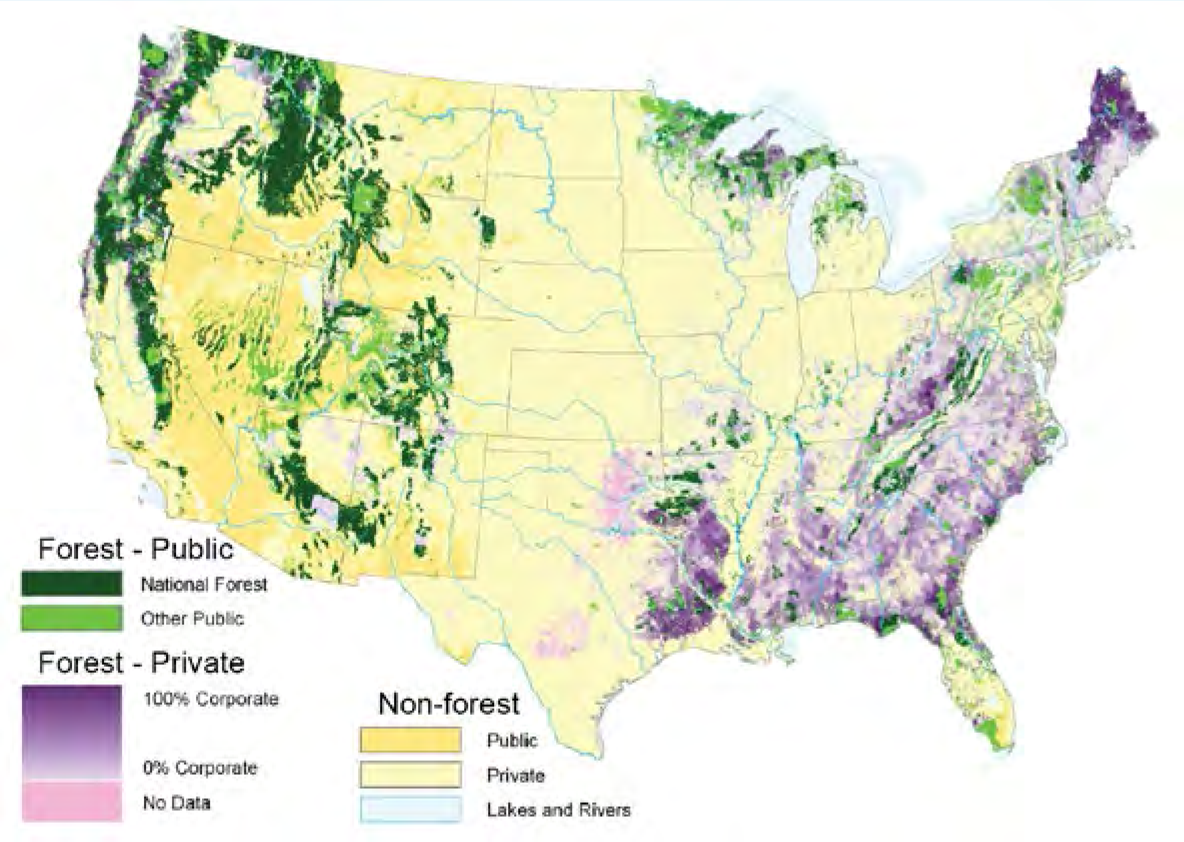

Figure 7.8. The figure shows forestland by ownership category in the contiguous U.S. in 2007.[41] Western forests are most often located on public lands, while eastern forests, especially in Maine and in the Southeast, are more often privately held. (Figure source: U.S. Forest Service 2012[41]).

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

A central component of the process was a workshop held in July 2011 by the U.S. Department of Agriculture Forest Service to guide the development of the technical input report (TIR). This session, along with numerous teleconferences, led to the foundational TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1]

The chapter authors engaged in multiple technical discussions via teleconference between January and June 2012, which included careful review of the foundational TIR and of 58 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Dale et al.[8] addressed a number of climate change factors that will affect U.S. forests and how they are managed. This is supported by additional publications focused on effects of drought and by more large-scale tree die-off events,[11,22] wildfire,[16,23,25] insects and pathogens. [11,22] Other studies support the negative impact of climate change by examining the tree mortality rate due to rising temperatures,[9,11,14,15,16,17,19,22] which is projected to increase in some regions.[22]

Although it is difficult to detect a trend in disturbances because they are inherently infrequent and it is impossible to attribute an individual disturbance event to changing climate, there is nonetheless much that past events, including recent ones, reveal about expected forest changes due to future climate. Observational[17] and experimental[22] studies show strong associations between forest disturbance and extreme climatic events and/or modifications in atmospheric evaporative demand related to warmer temperature. Regarding eastern forests, there are fewer observational or experimental studies, with Dietz and Moorcroft[18] being the most comprehensive.

Pollution and stand age are the most important factors in mortality. Tree survival increases with increased temperature in some groups. However, for other tree groups survival decreases with increased temperature.[18] In addition, this study[18] needs to be considered in the context that there have been fewer severe droughts in this region. However, physiological relationships suggest that trees will generally be more susceptible to mortality under an extreme drought, especially if it is accompanied by warmer temperatures.[13,68] Consequently, it is misleading to assume that, because eastern forests have not yet experienced the types of large-scale die-off seen in the western forests, they are not vulnerable to such events if an extreme enough drought occurs. Although the effect of temperature on the rate of mortality during drought has only been shown for one species,[22] the basic physiological relationships for trees suggest that warmer temperatures will exacerbate mortality for other species as well.[13,68]

Figure 7.1: This figure uses a figure from Goetz et al. 2012[7] which uses the MODIS Global Disturbance Index (MGDI) results from 2005 to 2009 to illustrate the geographic distribution of major ecosystem disturbance types across North America (based on Mildrexler et al. 2007, 2009[6,69]). The MGDI uses remotely sensed information to assess the intensity of the disturbance. Following the occurrence of a major disturbance, there will be a reduction in Enhanced Vegetation Index (EVI) because of vegetation damage; in contrast, Land Surface Temperature (LST) will increase because more absorbed solar radiation will be converted into sensible heat as a result of the reduction in evapotranspiration from less vegetation density. MGDI takes advantage of the contrast changes in EVI and LST following a disturbance to enhance the signal to ef-

fectively detect the location and intensity of disturbances (http://www.ntsg.umt.edu/project/mgdi). Moderate severity disturbance is mapped in orange and represents a 65%-100% divergence of the current-year MODIS Global Disturbance Index value from the range of natural variability, High severity disturbance (in red) signals a divergence of over 100%.[7]

New information and remaining uncertainties

Forest disturbances have large ecosystem effects, but high interannual variability in regional fire and insect activity makes detection of trends more difficult than for changes in mean conditions.[20,21,70] Therefore, there is generally less confidence in assessment of future projections of disturbance events than for mean conditions (for example, growth under slightly warmer conditions).[21]

There are insufficient data on trends in windthrow, ice storms, hurricanes, and landslide-inducing storms to infer that these types of disturbance events are changing.

Factors affecting tree death, such as drought, warmer temperatures, and/or pests and pathogens are often interrelated, which means that isolating a single cause of mortality is rare.[11,12,13,17,22,68]

Assessment of confidence based on evidence

Very High. There is very high confidence that under projected climate changes there is high risk (high risk = high probability and high consequence) that western forests in the United States will be affected increasingly by large and intense fires that occur more frequently.[16,23,25] This is based on the strong relationships between climate and forest response, shown observationally[17] and experimentally.[22] Expected responses will increase substantially to warming and also in conjunction with other changes such as an increase in the frequency and/or severity of drought and amplification of pest and pathogen impacts. Eastern forests are less likely to experience immediate increases in wildfire unless/until a point is reached at which warmer temperatures, concurrent with seasonal dry periods or more protracted drought, trigger wildfires.

Confidence Level

Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

A recent study[3] has shown that forests are a big sink of CO_2 nationally. However, the permanence of this carbon sink is contingent on forest disturbance rates, which are changing, and on economic conditions that may accelerate harvest of forest biomass.[56] Market response can cause changes in the carbon source/sink dynamics through shifts in forest age,[39,40] land-use changes and urbanization that reduce forested areas,[41] forest type changes,[42] and bioenergy development changing forest management.[41,43,44,45] Additionally, publications have reported that fires can convert a forest into a shrubland or meadow,[25] with frequent fires permanently reducing the carbon stock.[49]

New information and remaining uncertainties

That economic factors and societal choices will affect future carbon cycle of forests is known with certainty; the major uncertainties come from the future economic picture, accelerating disturbance rates, and societal responses to those dynamics.

Assessment of confidence based on evidence

Based on the evidence and uncertainties, confidence is **high** that climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake in the U.S. The U.S. has already seen large-scale shifts in forest cover due to interactions between forestland use and agriculture (for example, between the onset of European settlement to the present). There are competing demands for how forestland is used today. The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (Key Message 1), growth rates, and harvest demands.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Studies have shown that harvesting forest bioenergy can prevent carbon emissions[55] and replace a portion of U.S. energy consumption to help reduce future climate change. Some newer literature has explored how use of forest bioenergy can replace a portion of current U.S. energy production from oil.[20,45] Some more recent publications have reported some environmental benefits, such as improved water quality[56,57] and better management of timber lands,[45] that can result from forest bioenergy implementation.

New information and remaining uncertainties

The implications of forest product use for bioenergy depends on regional context and circumstances, such as feedstock type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution and use.[58]

The potential for biomass energy to increase forest harvests has led to debates about whether biomass energy is net carbon neutral.[59] The debate on biogenic emissions regulations revolves around how to account for emissions related to biomass production and use.[60] Deforestation contributes to atmospheric CO_2 concentration, and that contribution has been declining over time. The bioenergy contribution question is largely one of incentives for appropriate management. When forests have no value, they are burned or used inappropriately. Bioenergy can be produced in a way that provides more benefits than costs or vice versa. The market for energy from biomass appears to be ready to grow in response to energy pricing, policy, and demand; however, this industry is yet to be made a large-scale profitable enterprise in most regions of the United States.

Assessment of confidence based on evidence

High. Forest growth substantially exceeds annual harvest for normal wood and paper products, and much forest harvest residue is now unutilized. Forest bioenergy will become viable if policy and economic energy valuations make it competitive with fossil fuels.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The forest management response to climate change in urban areas, the wildland-urban interface, and in rural areas has been studied from varying angles. The literature on urban forests identifies the value of those forests to clean air, aesthetics, and recreation and suggests that under a changing climate, urban communities will continue to enhance their environment with trees and urban forests.[1,41] In the wildland-urban area and the rural areas, the changing composition of private forest landowners will affect the forest management response to climate change. Shifts in corporate owners to include investment organizations that may or may not have forest management as a primary objective has been described nationally.[1,2] Family forest owners are an aging demographic; one in five acres of forestland is owned by someone who is at least 75 years of age.[62] Multiple reasons for ownership are given by family forest owners, including the most commonly cited reasons of beauty/scenery, to pass land on to heirs, privacy, nature protection, and part of home/cabin. Many family forest owners feel it is necessary to keep the woods healthy but many are not familiar with forest management practices.[62] Long-term studies of the forest sector in the southern United States document the adaptive response of forest landowners to market prices as they manage to supply wood and associated products from their forests;[64] however prices are less of an incentive in other parts of the United States.[1,41] Econometric approaches have been used to explore the economic activities in the forest sector, including interactions with other sectors such as agriculture, impact of climate change, and the potential for new markets with bioenergy.[43,44] An earlier study explored the effects of globalization on forest management[63] and a newer study looked at the effect of U.S. climate change policy.[67] One of the biggest challenges is the lack of climate change information that results in inaction from many forest owners.[62]

New information and remaining uncertainties

Human concerns regarding the effects of climate change on forests and the role of adaptation and mitigation will be viewed from the perspective of the values that forests provide to human populations, including timber products, water, recreation, and aesthetic and spiritual benefits.[1] Many people, organizations, institutions, and governments influence the management of U.S. forests. Economic opportunities influence the amount and nature of private forestland (and much is known quantitatively about this dynamic) and societal values have a strong influence on how public forestland is managed. However, it remains challenging to project exactly how humans will respond to climate change in terms of forest management.

Climate change will alter known environmental and economic risks and add new risks to be addressed in the management of forests in urban areas, the wildland-urban interface, and rural areas. The capacity to manage risk varies greatly across landowners. While adaptation strategies provide a means to manage risks associated with climate change, a better understanding of risk perception by forest landowners would enhance the development and implementation of these management strategies. Identification of appropriate monitoring information and associated tools to evaluate monitoring data could facilitate risk assessment. Information and tools to assess environmental and economic risks associated with the impacts of climate change in light of specific management decisions would be informative to forestland managers and owners.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainty, there is **medium** confidence in this key message. Climate change and global and national economic events will have an integral impact on forest management, but it is uncertain to what magnitude. While forest landowners have shown the capacity to adapt to new economic conditions, potential changes in the international markets coincident with large-scale natural disturbances enhanced by climate change (fire, insects) could challenge this adaptive capacity. An important uncertainty is how people will respond to climate change in terms of forest management.

Climate Change Impacts in the United States

CHAPTER 8
ECOSYSTEMS,
BIODIVERSITY, AND ECOSYSTEM SERVICES

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

8 ECOSYSTEMS, BIODIVERSITY, AND ECOSYSTEM SERVICES

Key Messages

1. **Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.**
2. **Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.**
3. **Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.**
4. **Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.**
5. **Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.**

Climate change affects the living world, including people, through changes in ecosystems, biodiversity, and ecosystem services. Ecosystems entail all the living things in a particular area as well as the non-living things with which they interact, such as air, soil, water, and sunlight.[1] Biodiversity refers to the variety of life, including the number of species, life forms, genetic types, and habitats and biomes (which are characteristic groupings of plant and animal species found in a particular climate). Biodiversity and ecosystems produce a rich array of benefits that people depend on, including fisheries, drinking water, fertile soils for growing crops, climate regulation, inspiration, and aesthetic and cultural values.[2] These benefits are called "ecosystem services" – some of which, like food, are more easily quantified than others, such as climate regulation or cultural values. Changes in many such services are often not obvious to those who depend on them.

Ecosystem services contribute to jobs, economic growth, health, and human well-being. Although we interact with ecosystems and ecosystem services every day, their linkage to climate change can be elusive because they are influenced by so many additional entangled factors.[3] Ecosystem perturbations driven by climate change have direct human impacts, including reduced water supply and quality, the loss of iconic species and landscapes, distorted rhythms of nature, and the potential for extreme events to overwhelm the regulating services of ecosystems. Even with these well-documented ecosystem impacts, it is often difficult to quantify human vulnerability that results from shifts in ecosystem processes and services. For example, although it is more straightforward to predict how precipitation will change water flow, it is much harder to pinpoint which farms, cities, and habitats will be at risk of running out of water, and even more difficult to say how people will be affected by the loss of a favorite fishing spot or a wildflower that no longer blooms in the region. A better understanding of how a range of ecosystem responses affects people – from altered water flows to the loss of wildflowers – will help to inform the management of ecosystems in a way that promotes resilience to climate change.


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Forests absorb carbon dioxide and provide many other ecosystem services, such as purifying water and providing recreational opportunities.

Key Message 1: Water

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Climate-driven factors that control water availability and quality are moderated by ecosystems. Land-based ecosystems regulate the water cycle and are the source of sediment and other materials that make their way to aquatic ecosystems (streams, rivers, lakes, estuaries, oceans, groundwater). Aquatic ecosystems provide the critically important services of storing water, regulating water quality, supporting fisheries, providing recreation, and carrying water and materials downstream (Ch. 25: Coasts). Humans utilize, on average, the equivalent of more than 40% of renewable supplies of freshwater in more than 25% of all U.S. watersheds.[4] Freshwater withdrawals are even higher in the arid Southwest, where the equivalent of 76% of all renewable freshwater is appropriated by people.[5] In that region, climate change has likely decreased and altered the timing of streamflow due to reduced snowpack and lower precipitation in spring, although the precipitation trends are weak due to large year-to-year variability, as well as geographic variation in the patterns (Ch. 3: Water; Ch. 20: Southwest).[6] Depriving ecosystems of water reduces their ability to provide water to people as well as for aquatic plant and animal habitat (see Figure 8.1).

Habitat loss and local extinctions of fish and other aquatic species are projected from the combined effects of increased water withdrawal and climate change.[7] In the U.S., 47% of trout habitat in the interior West would be lost by 2080 under a scenario (A1B) that assumes similar emissions to the A2 scenario used in this report (Ch. 1: Overview, Ch. 2: Our Changing Climate) through 2050, and a slow decline thereafter.[8]

Across the entire U.S., precipitation amounts and intensity and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) (Ch. 3: Water).[9] At high concentrations, nutrients that are required for life (such as nitrogen and phosphorus) can become pollutants and can promote excessive phytoplankton growth – a process known as eutrophication. Currently, many U.S. lakes and rivers are polluted (have concentrations above government standards) by excessive nitrogen, phosphorus, or sediment. There are well-established links among fertilizer use, nutrient pollution, and river discharge, and many studies show that recent increases in rainfall in several regions of the United States have led to higher nitrogen amounts carried by rivers (Northeast,[10,11] California,[12] and Mississippi Basin[13,14]). Over the past 50 years, due to both climate and land-use change, the Mississippi Basin is yielding an additional 32 million acre-feet of water each year – equivalent to four Hudson Rivers – laden with materials washed from its farmlands.[15] This flows into the Gulf of Mexico, which is the site of the nation's largest hypoxic (low oxygen) "dead" zone.[4] The majority of U.S. estuaries are moderately to highly eutrophic.[16]

Links between discharge and sediment transport are well established,[17] and cost estimates for in-stream and off-stream damages from soil erosion range from $2.1 to $10 billion per year.[18,19] These estimates include costs associated with damages to, or losses of, recreation, water storage, navigation, commercial fishing, and property, but do not include costs of biological impacts.[18] Sediment transport, with accompanying nutrients, can play a positive role in the shoreline dynamics of coastlines and the life cycles of coastal and marine plants and animals. However, many commercially and recreationally important fish species such as salmon and trout that lay their eggs in the gravel at the edges of streams are especially sensitive to elevated sediment fluxes in rivers.[20] Sediment loading in lakes has been shown to have substantial detrimental effects on fish population sizes, community composition, and biodiversity.[21]


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Dissolved organic carbon (DOC) fluxes to rivers and lakes are strongly driven by precipitation;[22] thus in many regions where precipitation is expected to increase, DOC loading will also increase. Dissolved organic carbon is the substance that gives many rivers and lakes a brown, tea-colored look. Precipitation-driven increases in DOC concentration not only increase the cost of water treatment for municipal use,[23] but also alter the ability of sunlight to act as nature's water treatment plant. For example, *Cryptosporidium*, a pathogen potentially lethal to the elderly, babies, and people with compromised immune systems, is present in 17% of drinking water supplies sampled in the United States.[24] This pathogen is inactivated by doses of ultraviolet (UV) light equivalent to less than a day of sun exposure.[25] Similarly, UV exposures reduce fungal parasites that infect *Daphnia*, a keystone aquatic grazer and food source for fish.[26] Increasing DOC concentrations may thus reduce the ability of sunlight to regulate these UV-sensitive parasites.

Few studies have projected the impacts of climate change on nitrogen, phosphorus, sediment, or DOC transport from the land to rivers. However, given the tight link between river discharge and all of these potential pollutants, areas of the United States that are projected to see increases in precipitation, and increases in intense rainfalls, like the Northeast, Midwest, and mountainous West,[27] will also see increases in excess nutrients, DOC, and sediments transported to rivers. One of the few future projections available suggests that downstream and coastal impacts of increased nitrogen inputs could be profound for the Mississippi Basin. Under a scenario in which atmospheric CO_2 reaches double pre-industrial levels, a 20% increase in river discharge is expected to lead to higher nitrogen loads and a 50% increase in algae growth in the Gulf of Mexico, a 30% to 60% decrease in deep-water dissolved oxygen concentration, and an expansion of the dead zone.[28] A recent comprehensive assessment[10] shows that, while climate is an important driver, nitrogen carried by rivers to the oceans is most strongly driven by fertilizer inputs to the land. Therefore, in the highly productive agricultural systems of the Mississippi Basin, the ultimate impact of more precipitation on the expansion of the dead zone will depend on agricultural management practices in the Basin.[14,29]

Rising air temperatures can also lead to declines in water quality through a different set of processes. Some large lakes, including the Great Lakes, are warming rapidly.[30] Warmer surface waters can stimulate blooms of harmful algae in both lakes and coastal oceans,[9] which may include toxic cyanobacteria that are favored at higher temperatures.[31] Harmful algal blooms, which are caused by many factors, including climate change, exact a cost in freshwater degradation of approximately $2.2 billion annually in the United States alone.[32]

Water Supplies Projected to Decline

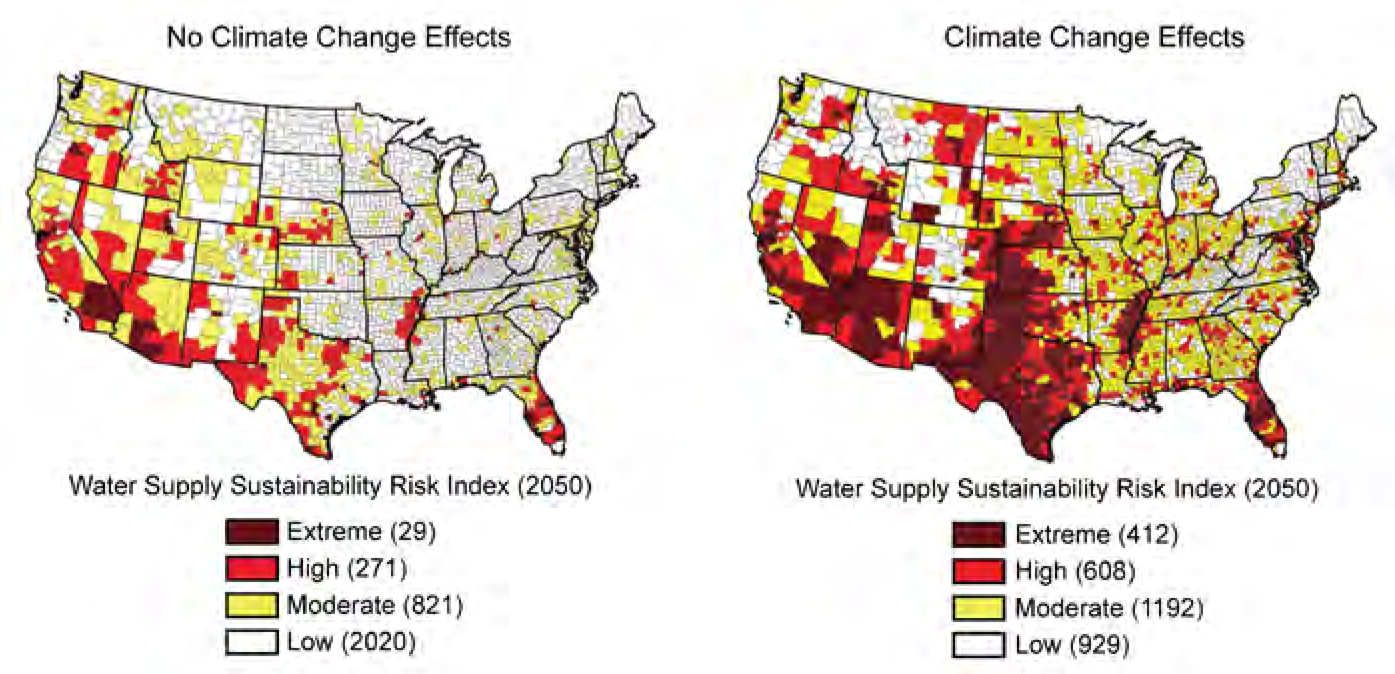


Figure 8.1. Climate change is projected to reduce the ability of ecosystems to supply water in some parts of the country. This is true in areas where precipitation is projected to decline, and even in some areas where precipitation is expected to increase. Compared to 10% of counties today, by 2050, 32% of counties will be at high or extreme risk of water shortages. Projections assume continued increases in greenhouse gas emissions through 2050 and a slow decline thereafter (A1B scenario). Numbers in parentheses indicate number of counties in each category. (Reprinted with permission from Roy et al., 2012.[27] Copyright 2012 American Chemical Society).

The Aftermath of Hurricanes

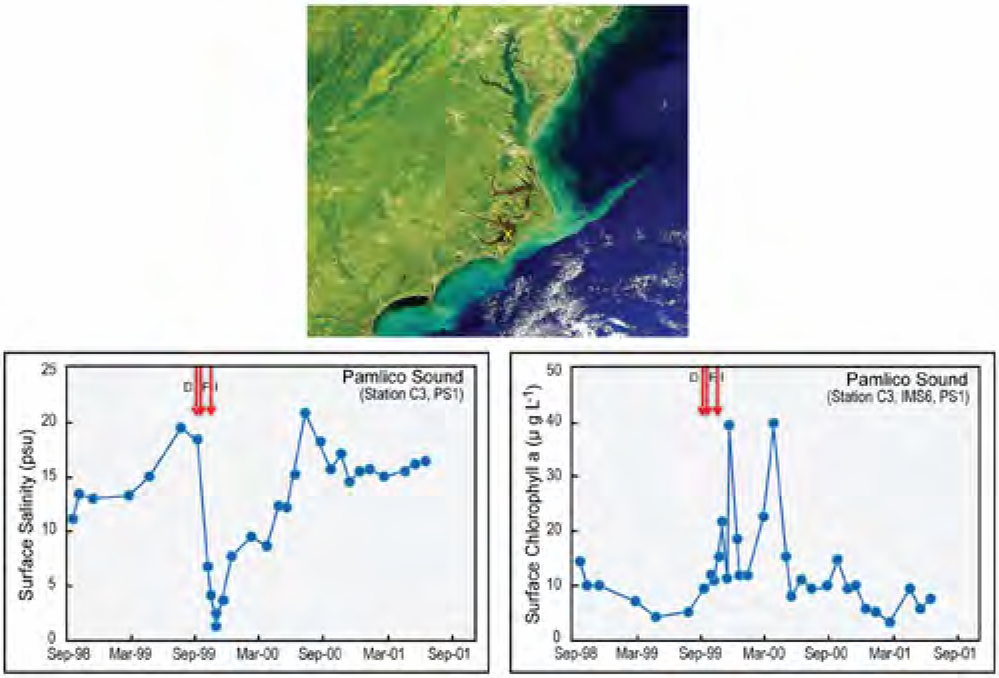


Figure 8.2. Hurricanes illustrate the links among precipitation, discharge and nutrient loading to coastal waters. Hurricanes bring intense rainfall to coastal regions, and ensuing runoff leads to blooms of algae. These blooms contribute to dead zone formation after they die and decompose. Photo above shows Pamlico Sound, North Carolina, after Hurricane Floyd. Note light green area off the coast, which is new algae growth. The graph on the left shows a steep drop in salinity of ocean water due to the large influx of freshwater from rain after a series of hurricanes. Red arrows indicate Hurricanes Dennis, Floyd, and Irene, which hit sequentially during the 1999 hurricane season. The graph on the right shows a steep rise in the amount of surface chlorophyll after these hurricanes, largely due to increased algae growth. (Figure source: (top) NASA SeaWiFS; (bottom) Paerl et al. 2003[33]).

Key Message 2: Extreme Events

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Ecosystems play an important role in "buffering" the effects of extreme climate conditions (floods, wildfires, tornadoes, hurricanes) on the movement of materials and the flow of energy through the environment.[34] Climate change and human modifications often increase the vulnerability of ecosystems and landscapes to damage from extreme events while at the same time reducing their natural capacity to modulate the impacts of such events. Salt marshes, reefs, mangrove forests, and barrier islands provide an ecosystem service of defending coastal ecosystems and infrastructure against storm surges.[35] Losses of these natural features – from coastal development, erosion, and sea level rise – render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (Ch. 25: Coasts).[36] Floodplain wetlands, although greatly reduced from their historical extent, provide an ecosystem service of absorbing floodwaters and reducing the impact of high flows on river-margin lands. In the Northeast, even a small sea level rise (1.6 feet) would dramatically increase the numbers of people (47% increase) and property loss (73% increase) affected by storm surge in Long Island compared to present day storm surge impacts.[37] Extreme weather events that produce sudden increases in water flow and the materials it carries can decrease the natural capacity of ecosystems to process pollutants, both by reducing the amount of time water is in contact with reactive sites and by removing or harming the plants and microbes that remove the pollutants.[36]

Warming and, in some areas, decreased precipitation (along with past forest fire suppression practices) have increased the risk of fires exceeding historical size, resulting in unprecedented social and economic challenges. Large fires put people living in the wildland-urban interface at risk for health problems and property loss. In 2011 alone, more than 8 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

Key Message 3: Plants and Animals

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Vegetation model projections suggest that much of the United States will experience changes in the composition of species characteristic of specific areas. Studies applying different models for a range of future climates project biome changes for about 5% to 20% of the land area of the U.S. by 2100.[4,39] Many major changes, particularly in the western states and Alaska, will in part be driven by increases in fire frequency and severity. For example, the average time between fires in the Yellowstone National Park ecosystem is projected to decrease from 100 to 300 years to less than 30 years, potentially causing coniferous (pine, spruce, etc.) forests to be replaced by woodlands and grasslands.[40] Warming has also led to novel wildfire occurrence in ecosystems where it has been absent in recent history, such as arctic Alaska and the southwestern deserts where new fires are fueled by non-native annual grasses (Ch. 20: Southwest; Ch. 22: Alaska). Extreme weather conditions linked to sea ice decline in 2007 led to the ignition of the Anaktuvuk River Fire, which burned more than 380 square miles of arctic tundra that had not been disturbed by fire for more than 3,000 years.[41] This one fire (which burned deeply into organic peat soils) released enough carbon to the atmosphere to offset all of the carbon taken up by the entire arctic tundra biome over the past quarter-century.[42]

In addition to shifts in species assemblages, there will also be changes in species distributions. In recent decades, in both land and aquatic environments, plants and animals have moved to higher elevations at a median rate of 36 feet (0.011 kilometers) per decade, and to higher latitudes at a median rate of 10.5 miles (16.9 kilometers) per decade.[43] As the climate continues to change, models and long-term studies project even greater shifts in species ranges.[44] However, many species may not be able to keep pace with climate change for several reasons, for example because their seeds do not disperse widely or because they have limited mobility, thus leading, in some places, to local extinctions of both plants and animals. Both range shifts and local extinctions will, in many places, lead to large changes in the mix of plants and animals present in the local ecosystem, resulting in new communities that bear little resemblance to those of today.[4,8,45,46]

Some of the most obvious changes in the landscape are occurring at the boundaries between biomes. These include shifts in the latitude and elevation of the boreal (northern) forest/tundra boundary in Alaska;[47] elevation shifts of the boreal and subalpine forest/tundra boundary in the Sierra Nevada, California;[48] an elevation shift of the temperate broadleaf/conifer boundary in the Green Mountains, Vermont,[49] the shift of temperate the shrubland/conifer forest boundary in Bandelier National Monument, New Mexico,[50] and upslope shifts of the temperate mixed forest/conifer boundary in Southern California.[51] All of these are consistent with recent climatic trends and represent visible changes, like tundra switching to forest, or conifer forest switching to broadleaf forest or even to shrubland.

As temperatures rise and precipitation patterns change, many fish species (such as salmon, trout, whitefish, and char) will be lost from lower-elevation streams, including a projected loss of 47% of habitat for all trout species in the western U.S. by 2080.[8] Similarly, in the oceans, transitions from cold-water fish communities to warm-water communities have occurred in commercially important harvest areas,[52] with new industries developing in response to the arrival of new species.[53] Also, warm surface waters are driving some fish species to deeper waters.[54,55]

Warming is likely to increase the ranges of several invasive plant species in the United States,[56] increase the probability of establishment of invasive plant species in boreal forests in south-central Alaska, including the Kenai Peninsula,[57] and expand the range of the hemlock wooly adelgid, an insect that has killed many eastern hemlocks in recent years.[58] Invasive species costs to the U.S. economy are estimated at $120 billion per year,[59] including substantial impacts on ecosystem services. For instance, the yellow star-thistle, a wildland pest which is predicted to thrive with increased atmospheric CO_2,[60] currently costs California ranchers and farmers $17 million in forage and control efforts[61] and $75 million in water losses.[62] Iconic desert species such as saguaro cactus are damaged or killed by fires fueled by non-native grasses, leading to a large-scale transformation of desert shrubland into grassland in many of the familiar landscapes of the American West.[63] Bark beetles have infested extensive areas of the western United States and Canada, killing stands of temperate and boreal conifer forest across areas greater than any other outbreak in the last 125 years.[64] Climate change has been a major causal factor, with higher temperatures allowing more beetles to survive winter, complete two life cycles in a season rather than one, and to move to higher elevations and latitudes.[64,65] Bark beetle outbreaks in the Greater Yellowstone Ecosystem are occurring in habitats where outbreaks either did not previously occur or were limited in scale.[66]

It is important to realize that climate change is linked to far more dramatic changes than simply altering species' life cycles or shifting their ranges. Several species have exhibited population declines linked to climate change, with some declines so severe that species are threatened with extinction.[67] Perhaps the most striking impact of climate change is its effect on iconic species such as the polar bear, the ringed seal, and coral species (Ch. 22: Alaska; Ch. 24: Oceans). In 2008, the polar bear (*Ursus maritimus*) was listed as a threatened species, with the primary cause of its decline attributed to climate change.[68] In 2012, NOAA determined that four subspecies of the ringed seal (*Phoca hispida*) were threatened or endangered, with the primary threat being climate change.[69]

Key Message 4: Seasonal Patterns

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

The effect of climate change on phenology – the pattern of seasonal life cycle events in plants and animals, such as timing of leaf-out, blooming, hibernation, and migration – has been called a "globally coherent fingerprint of climate change impacts" on plants and animals.[70] Observed long-term trends towards shorter, milder winters and earlier spring thaws are altering the timing of critical spring events such as bud burst and emergence from overwintering. This can cause plants and animals to be so out of phase with their natural phenology that outbreaks of pests occur, or species cannot find food at the time they emerge.

Recent studies have documented an advance in the timing of springtime phenological events across species in response to increased temperatures.[71] Long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures[72] and by 1.5 days per decade earlier in the western United States.[73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] In addition, plant-pollinator relationships may be disrupted by changes in nectar and pollen availability, as the timing of bloom shifts in response to temperature and precipitation.[76,77]

As spring is advancing and fall is being delayed in response to regional changes in climate,[78] the growing season is lengthening. A longer growing season will benefit some crops and natural species, but there may be a timing mismatch between the microbial activity that makes nutrients available in the soil and the readiness of plants to take up those nutrients for growth.[78,79] Where plant phenology is driven by day length, an advance in spring may exacerbate this mismatch, causing available nutrients to be leached out of the soil rather than absorbed and recycled by plants.[80] Longer growing seasons also exacerbate human allergies. For example, a longer fall allows for bigger ragweed plants that produce more pollen later into the fall (see also Ch. 9: Health).[81]

Changes in the timing of springtime bird migrations are well-recognized biological responses to warming, and have been documented in the western,[82] midwestern,[83] and eastern United States.[84,85] Some migratory birds now arrive too late for the peak of food resources at breeding grounds because temperatures at wintering grounds are changing more slowly than at spring breeding grounds.[86]

In a 34-year study of an Alaskan creek, young pink salmon (*Oncorhynchus gorbuscha*) migrated to the sea increasingly earlier over time.[87] In Alaska, warmer springs have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou (*Rangifer tarandus*).

Key Message 5: Adaptation

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Adaptation in the context of biodiversity and natural resource management is fundamentally about managing change, which is an inherent property of natural ecosystems.[4,88,89] One strategy – adaptive management, which is a structured process of flexible decision-making under uncertainty that incorporates learning from management outcomes – has received renewed attention as a tool for helping resource managers make decisions relevant to whole systems in response to climate change.[89,90] Other strategies tinclude assessments of vulnerability and impacts,[91] and scenario planning,[92] that can be assembled into a general planning process that is flexible and iterative.

Guidance on adaptation planning for conservation has proliferated at the federal[92,93,94] and state levels,[95] and often emphasizes cooperation between scientists and managers.[94,96,97] Ecosystem-based adaptation[98,99] uses "biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change."[99] An example is the explicit use of storm-buffering coastal wetlands or mangroves rather than built infrastructure like seawalls or levies to protect coastal regions (Ch. 25: Coasts).[100] An additional example is the use of wildlife corridors to connect fragmented wildlife habitat.[101]

Adaptation strategies to protect biodiversity include: 1) habitat manipulation, 2) conserving populations with higher genetic diversity or more flexible behaviors or morphologies, 3) re-planting with species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) offsite conservation such as seed banking, biobanking, and captive breeding.[92,94,96,97,102,103] Additional approaches focus on identifying and protecting features that are important for biodiversity and are less likely to be altered by climate change. The idea is to conserve the "stage" (the biophysical conditions that contribute to high levels of biodiversity) for whatever "actors" (species and populations) find those areas suitable in the future.[104]

One of the greatest challenges for adaptation in the face of climate change is the revision of management goals in fundamental ways. In particular, not only will climate change make it difficult to achieve existing conservation goals, it will demand that goals be critically examined and potentially altered in dramatic ways.[102,105] Climate changes can also severely diminish the effectiveness of current strategies and require fresh approaches. For example, whereas establishing networks of nature reserves has been a standard approach to protecting species, fixed networks of reserve do not lend themselves to adjustments for climate change.[105] Finally, migratory species and species with complex life histories cannot be simply addressed by defining preferred habitat and making vulnerability assessments. Often it could be specific life history stages that are the weak point in the species, and it is key to identify those weak links.[106]

While there is considerable uncertainty about how climate change will play out in particular locations, proactive measures can be taken to both plan for connectivity[96,107] and to identify places or habitats that may in the future become valuable habitat as a result of climate change and vegetation shifts.[108] It is important to note that when the Endangered Species Act (ESA) was passed in 1973, climate change was not a known threat or factor and was not considered in setting recovery goals or critical habitat designations.[109] However, agencies are actively working to include climate change considerations in their ESA implementation activities.

Adaptation Planning and Implementation Framework

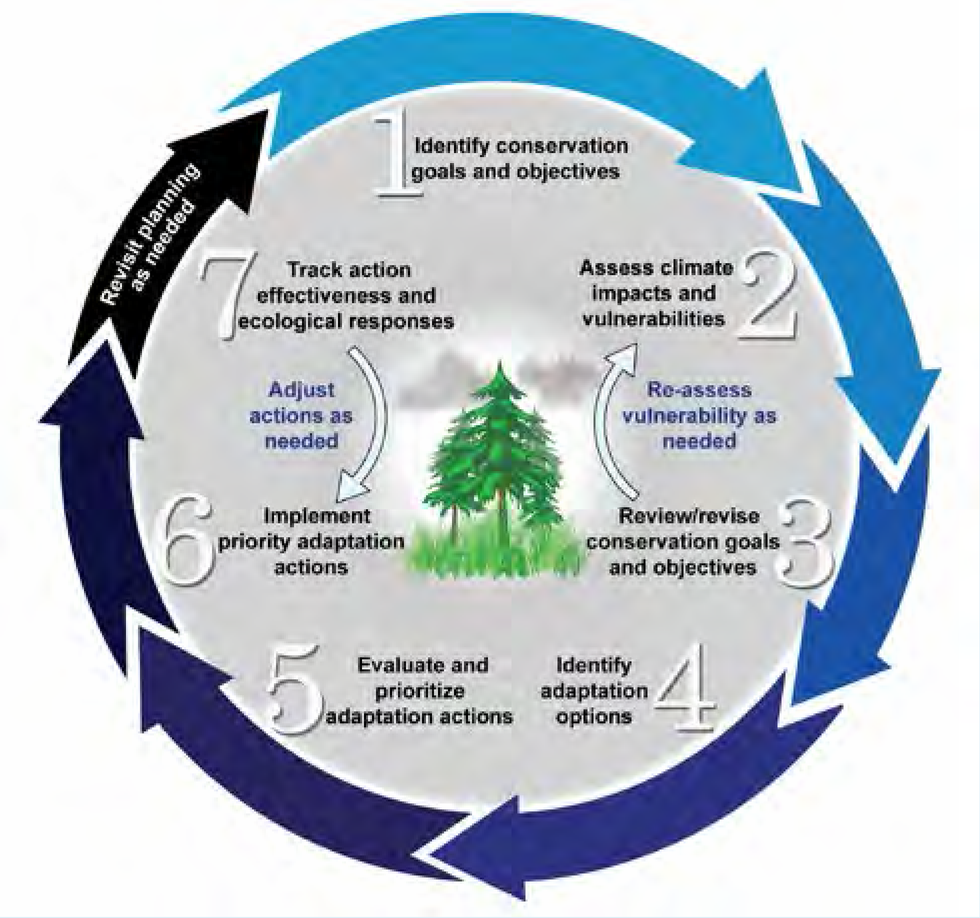


Figure 8.3. Iterative approaches to conservation planning require input and communication among many players to ensure flexibility in response to climate change. (Figure source: adapted from the National Wildlife Federation, 2013[142]).

CASE STUDY OF THE 2011 LAS CONCHAS, NEW MEXICO FIRE

In the midst of severe drought in the summer of 2011, Arizona and New Mexico suffered the largest wildfires in their recorded history, affecting more than 694,000 acres. Some rare threatened and endangered species, like the Jemez salamander, were damaged by this unusually severe fire.[110] Fires are often part of the natural disturbance regime, but if drought, poor management, and high temperatures combine, a fire can be so severe and widespread that species are damaged that otherwise might even be considered to be fire tolerant (such as spotted owls). Following the fires, heavy rainstorms led to major flooding and erosion, including at least ten debris flows. Popular recreation areas were evacuated and floods damaged the newly renovated, multi-million dollar U.S. Park Service Visitor Center at Bandelier National Monument. Sediment and ash eroded by the floods were washed downstream into the Rio Grande, which supplies 50% of the drinking water for Albuquerque, the largest city in New Mexico. Water withdrawals by the city from the Rio Grande were stopped entirely for a week and reduced for several months due to the increased cost of treatment.

These fires provide an example of how forest ecosystems, biodiversity, and ecosystem services are affected by the impacts of climate change, other environmental stresses, and past management practices. Higher temperatures, reduced snowpack, and earlier onset of springtime are leading to increases in wildfire in the western United States,[111] while extreme droughts are becoming more frequent.[112] In addition, climate change is affecting naturally occurring bark beetles: warmer winter conditions allow these pests to breed more frequently and successfully.[113,114] The dead trees left behind by bark beetles may make crown fires more likely, at least until needles fall from killed trees.[114,115] Forest management practices also have made the forests more vulnerable to catastrophic fires. In New Mexico, even-aged, second-growth forests were hit hardest because they are much denser than naturally occurring forest and consequently consume more water from the soil and increase the availability of dry above-ground fuel.

BIOLOGICAL RESPONSES TO CLIMATE CHANGE

Figure 8.4. Map of selected observed and projected biological responses to climate change across the United States. Case studies listed below correspond to observed responses (black icons on map) and projected responses (white icons on map, bold italicized statements). In general, because future climatic changes are projected to exceed those experienced in the recent past, projected biological impacts tend to be of greater magnitude than recent observed changes. Because the observations and projections presented here are not paired (that is, they are not for the same species or systems), that general difference is not illustrated. (Figure source: Staudinger et al., 2012[4]).

Continued

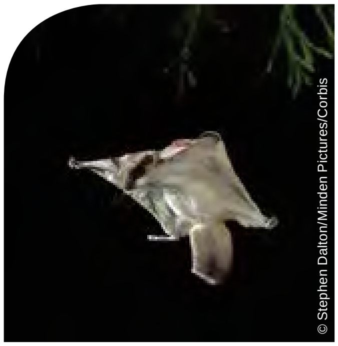
BIOLOGICAL RESPONSES TO CLIMATE CHANGE (CONTINUED)

1. Mussel and barnacle beds have declined or disappeared along parts of the Northwest coast due to higher temperatures and drier conditions that have compressed habitable intertidal space.[116]
2. Northern flickers arrived at breeding sites earlier in the Northwest in response to temperature changes along migration routes, and egg laying advanced by 1.15 days for every degree increase in temperature, demonstrating that this species has the capacity to adjust their phenology in response to climate change.[117]
3. Conifers in many western forests have experienced mortality rates of up to 87% from warming-induced changes in the prevalence of pests and pathogens and stress from drought.[118]
4. Butterflies that have adapted to specific oak species have not been able to colonize new tree species when climate change-induced tree migration changes local forest types, potentially hindering adaptation.[119]
5. In response to climate-related habitat change, many small mammal species have altered their elevation ranges, with lower-elevation species expanding their ranges and higher-elevation species contracting their ranges.[120]
6. ***Northern spotted owl populations in Arizona and New Mexico are projected to decline during the next century and are at high risk for extinction due to hotter, drier conditions, while the southern California population is not projected to be sensitive to future climatic changes.***[121]
7. Quaking aspen-dominated systems are experiencing declines in the western U.S. after stress due to climate-induced drought conditions during the last decade.[122]
8. Warmer and drier conditions during the early growing season in high-elevation habitats in Colorado are disrupting the timing of various flowering patterns, with potential impacts on many important plant-pollinator relationships.[77]
9. ***Population fragmentation of wolverines in the northern Cascades and Rocky Mountains is expected to increase as spring snow cover retreats over the coming century.***[123]
10. ***Cutthroat trout populations in the western U.S. are projected to decline by up to 58%, and total trout habitat in the same region is projected to decline by 47%, due to increasing temperatures, seasonal shifts in precipitation, and negative interactions with non-native species.***[8]
11. Comparisons of historical and recent first flowering dates for 178 plant species from North Dakota showed significant shifts occurred in over 40% of species examined, with the greatest changes observed during the two warmest years of the study.[75]
12. Variation in the timing and magnitude of precipitation due to climate change was found to decrease the nutritional quality of grasses, and consequently reduce weight gain of bison in the Konza Prairie in Kansas and the Tallgrass Prairie Preserve in Oklahoma.[124] Results provide insight into how climate change will affect grazer population dynamics in the future.
13. (a and b) Climatic fluctuations were found to influence mate selection and increase the probability of infidelity in birds that are normally socially monogamous, increasing the gene exchange and the likelihood of offspring survival.[125]
14. Migratory birds monitored in Minnesota over a 40-year period showed significantly earlier arrival dates, particularly in short-distance migrants, indicating that some species are capable of responding to increasing winter temperatures better than others.[126]
15. ***Up to 50% turnover in amphibian species is projected in the eastern U.S. by 2100, including the northern leopard frog, which is projected to experience poleward and elevational range shifts in response to climatic changes in the latter quarter of the century.***[127]
16. ***Studies of black ratsnake (Elaphe obsoleta) populations at different latitudes in Canada, Illinois, and Texas suggest that snake populations, particularly in the northern part of their range, could benefit from rising temperatures if there are no negative impacts on their habitat and prey.***[128]
17. Warming-induced hybridization was detected between southern and northern flying squirrels in the Great Lakes region of Ontario, Canada, and in Pennsylvania after a series of warm winters created more overlap in their habitat range, potentially acting to increase population persistence under climate change.[129]

Continued

BIOLOGICAL RESPONSES TO CLIMATE CHANGE (CONTINUED)

18. Some warm-water fishes have moved northwards, and some tropical and subtropical fishes in the northern Gulf of Mexico have increased in temperate ocean habitat.[130] Similar shifts and invasions have been documented in Long Island Sound and Narragansett Bay in the Atlantic.[131]
19. ***Global marine mammal diversity is projected to decline at lower latitudes and increase at higher latitudes due to changes in temperatures and sea ice, with complete loss of optimal habitat for as many as 11 species by mid-century; seal populations living in tropical and temperate waters are particularly at risk to future declines.***[132]
20. Higher nighttime temperatures and cumulative seasonal rainfalls were correlated with changes in the arrival times of amphibians to wetland breeding sites in South Carolina over a 30-year time period (1978-2008).[133]
21. Seedling survival of nearly 20 resident and migrant tree species decreased during years of lower rainfall in the Southern Appalachians and the Piedmont areas, indicating that reductions in native species and limited replacement by invading species were likely under climate change.[134]
22. Widespread declines in body size of resident and migrant birds at a bird-banding station in western Pennsylvania were documented over a 40-year period; body sizes of breeding adults were negatively correlated with mean regional temperatures from the preceding year.[85]
23. Over the last 130 years (1880-2010), native bees have advanced their spring arrival in the northeastern U.S. by an average of 10 days, primarily due to increased warming. Plants have also showed a trend of earlier blooming, thus helping preserve the synchrony in timing between plants and pollinators.[135]
24. In the Northwest Atlantic, 24 out of 36 commercially exploited fish stocks showed significant range (latitudinal and depth) shifts between 1968 and 2007 in response to increased sea surface and bottom temperatures.[55]
25. Increases in maximum, and decreases in the annual variability of, sea surface temperatures in the North Atlantic Ocean have promoted growth of small phytoplankton and led to a reorganization in the species composition of primary (phytoplankton) and secondary (zooplankton) producers.[136]
26. Changes in female polar bear reproductive success (decreased litter mass and numbers of yearlings) along the north Alaska coast have been linked to changes in body size and/or body condition following years with lower availability of optimal sea ice habitat.[137]
27. Water temperature data and observations of migration behaviors over a 34-year time period showed that adult pink salmon migrated earlier into Alaskan creeks, and fry advanced the timing of migration out to sea. Shifts in migration timing may increase the potential for a mismatch in optimal environmental conditions for early life stages, and continued warming trends will likely increase pre-spawning mortality and egg mortality rates.[87]
28. Warmer springs in Alaska have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou. This ultimately reduced calving success in caribou populations.[138]
29. ***Many Hawaiian mountain vegetation types were found to vary in their sensitivity to changes in moisture availability; consequently, climate change will likely influence elevation-related vegetation patterns in this region.***[139]
30. ***Sea level is predicted to rise by 1.6 to 3.3 feet in Hawaiian waters by 2100, consistent with global projections of 1 to 4 feet of sea level rise (see Ch. 2: Our Changing Climate, Key Message 10). This is projected to increase wave heights, the duration of turbidity, and the amount of re-suspended sediment in the water; consequently, this will create potentially stressful conditions for coral reef communities.***[140]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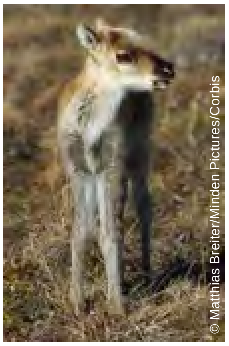
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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages and supporting chapter text summarize extensive evidence documented in the Ecosystems Technical Input Report, *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment*.[4] This foundational report evolved from a technical workshop held at the Gordon and Betty Moore Foundation in Palo Alto, CA, in January 2012 and attended by approximately 65 scientists. Technical inputs (127) on a wide range of topics related to ecosystems were also received and reviewed as part of the Federal Register Notice solicitation for public input.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Studies have shown that increasing precipitation is already resulting in declining water quality in many regions of the country, particularly by increasing nitrogen loading.[10,11,12,13,14] This is because the increases in flow can pick up and carry greater loads of nutrients like nitrogen to rivers.[11,12,13,14]

One model for the Mississippi River Basin, based on a doubling of CO_2, projects that increasing discharge and nitrogen loading will lead to larger algal blooms in the Gulf of Mexico and a larger dead zone.[28] The Gulf of Mexico is the recipient system for the Mississippi Basin, receiving all of the nitrogen that is carried downriver but not removed by river processes, wetlands, or other ecosystems.

Several models project that declining streamflow, due to the combined effects of climate change and water withdrawals, will cause local extinctions of fish and other aquatic organisms,[7] particularly trout in the interior western U.S. (composite of 10 models, A1B scenario).[8] The trout study[8] is one of the few studies of impacts on fish that uses an emissions scenario and a combination of climate models. The researchers studied four different trout species. Although there were variations among species, their overall conclusion was robust across species for the composite model.

Water quality can also be negatively affected by increasing temperatures. There is widespread evidence that warmer lakes can promote the growth of harmful algal blooms, which produce toxins.[31]

New information and remaining uncertainties

Recent research has improved understanding of the relative importance of the effects of climate and human actions (for example, fertilization) on nitrogen losses from watersheds,[10,12] and how the interactions between climate and human actions (for example, water withdrawals) will affect fish populations in the west.[7,8] However, few studies have projected the impacts of future climate change on water quality. Given the tight link between river discharge and pollutants, only areas of the U.S. that are projected to see increases in precipitation will see increases in pollutant transport to rivers. It is also important to note that pollutant loading – for example, nitrogen fertilizer use – is often more important as a driver of water pollution than climate.[10,12]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

It is well established that precipitation and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) transport into rivers. Increases in precipitation in many regions of the country are therefore contributing to declines in water quality in those areas. However, those areas of the country that will see reduced precipitation may experience water-quality improvement; thus, any lack of agreement on future water-quality impacts of climate change may be due to locational differences.

Confidence Level

Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Fires: Climate change has increased the potential for extremely large fires with novel social, economic, and environmental impacts. In 2011, more than 8 million acres burned, with significant human mortality and property damage ($1.9 billion).[38] Warming and decreased precipitation have made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss.

Floods: Natural ecosystems such as salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against flooding due to storm surges. The loss of these natural features due to coastal development, erosion, and sea level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (see Ch. 25: Coasts).[36] Floodplain wetlands, which are also vulnerable to loss by inundation, absorb floodwaters and reduce the impact of high flows on river-margin lands. In the Northeast, a sea level rise of 1.6 feet (within the range of 1 to 4 feet projected for 2100; Ch. 2: Our Changing Climate, Key Message 9) will dramatically increase impacts of storm surge on people (47% increase) and property loss (73% increase) in Long Island.[37]

Storms: Natural ecosystems have a capacity to buffer extreme weather events that produce sudden increases in water flow and materials. These events reduce the amount of time water is in contact with sites that support the plants and microbes that remove pollutants (Chapter 25: Coasts).[36]

New information and remaining uncertainties

A new analytical framework was recently developed to generate insights into the interactions among the initial state of ecosystems, the type and magnitude of disturbance, and effects of disturbance.[34] Progress in understanding these relationships is critical for predicting how human activities and climate change, including extreme events like droughts, floods, and storms, will interact to affect ecosystems.

Uncertainties: The ability of ecosystems to buffer extreme events is extremely difficult to assess and quantify, as it requires understanding of complex ecosystem responses to very rare events. However, it is clear that the loss of this buffering ecosystem service is having important effects on coastal and fire-prone ecosystems across the United States.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like droughts, floods, and storms.

Ecosystem responses to climate change will vary regionally. For example, whether salt marshes and mangroves will be able to accrue sediment at rates sufficient to keep ahead of sea level rise and maintain their protective function will vary by region.

Climate has been the dominant factor controlling burned area during the 20th century, even during periods of fire suppression by forest management,[40,111] and the area burned annually has increased steadily over the last 20 years concurrent with warming and/or drying climate. Warming and decreased precipitation have also made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss. In 2011 alone, 8.3 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

KEY MESSAGE #3 TRACEABLE ACCOUNT

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Description of evidence base

The analysis for the Technical Input Report applied a range of future climate scenarios and projected biome changes across 5% to about 20% of the land area in the U.S. by 2100.[4] Other analyses support these projections.[39] Studies predict that wildfire will be a major driver of change in some areas, including Yellowstone National Park[40] and the Arctic.[41] These biome shifts will be associated with changes in species distributions.[43]

Evidence indicates that the most obvious changes will occur at the boundaries between ecosystems.[47,48,49,51] Plants and animals are already moving to higher elevations and latitudes in response to climate change,[43] with models projecting greater range shifts[8,46] and local extinctions in the future, leading to new plant and animal communities that may be unrecognizable in some regions.[4,45,46] One study on fish[8] used global climate models (GCMs) simulating conditions in the 2040s and 2080s under the A1B emissions scenario, with the choice of models reflecting predictions of high and low climate warming as well as an ensemble of ten models. Their models additionally accounted for biotic interactions. In a second study, a 30-year baseline (1971-2000) and output from two GCMs under the A2 scenario (continued increases in global emissions) were used to develop climate variables that effectively predict present and future species ranges.[46] Empirical data from the Sonoran Desert (n=39 plots) were used to evaluate species responses to past climate variability.

Iconic species: Wildfire is expected to damage and kill iconic desert species, including saguaro cactus.[63] Bark beetle outbreaks, which have been exacerbated by climate change, are damaging extensive areas of temperate and boreal conifer forests that are characteristic of the western United States.[64]

New information and remaining uncertainties

In addition to the Technical Input Report, more than 20 new studies of observed and predicted effects of climate change on biomes and species distribution were incorporated in the assessment.

While changes in ecosystem structure and biodiversity, including the distribution of iconic species, are occurring and are highly likely to continue, the impact of these changes on ecosystem services is unclear, that is, there is uncertainty about the impact that loss of familiar landscapes will have on people.

Assessment of confidence based on evidence

Based on the evidence base and uncertainties, confidence is **high** that familiar landscapes are changing so rapidly that iconic species may disappear from regions where they have been prevalent, altering some regions so much that their mix of plant and animal life will become almost unrecognizable. Many changes in species distribution have already occurred and will inevitably continue, resulting in the loss of familiar landscapes and the production of novel species assemblages.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Ecosystems Technical Input, *Phenology as a bio-indicator of climate change impacts on people and ecosystems: Towards an integrated national assessment approach*.[71] An additional 127 input reports, on a wide range of topics related to ecosystems, were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Many studies have documented an advance in springtime phenological events of species in response to climate warming. For example, long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures, and by 1.5 days per decade earlier in the western United States.[72,73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] Evidence suggests that insect emergence from overwintering may become out of sync with pollen sources,[77] and that the beginning of bird and fish migrations are shifting.[82,83,84,85,86,87]

New information and remaining uncertainties

In addition to the Ecosystems Technical Input[71] many new studies have been conducted since the previous National Climate Assessment,[141] contributing to our understanding of the impacts of climate change on phenological events. Many studies, in many areas, have shown significant changes in phenology, including spring bud burst, emergence from overwintering, and migration shifts.

A key uncertainty is "phase effects" where organisms are so out of phase with their natural phenology that outbreaks of pests occur, species emerge and cannot find food, or pollination is disrupted. This will vary with specific species and is therefore very difficult to predict.[70]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is very high confidence that the timing of critical events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Description of evidence base

Adaptation planning for conservation at federal[92,93,94] and state levels,[95] is focused on cooperation between scientists and managers.[34,94,96,97] Development of ecosystem-based whole system management[98] utilizes concepts about "biodiversity and ecosystem services to help people adapt to climate change."[99] An example is the use of coastal wetlands or mangroves rather than built infrastructure like seawalls or levees to protect coastal regions from storms (Chapter 25: Coasts).[100]

New information and remaining uncertainties

Adaptation strategies to protect biodiversity include: 1) habitat manipulations, 2) conserving populations with higher genetic diversity or more plastic behaviors or morphologies, 3) changing seed sources for re-planting to introduce species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) ex-situ conservation such as seed banking and captive breeding.[92,94,96,97,102] Alternative approaches focus on identifying and protecting features that are important for biodiversity and are projected to be less altered by climate change. The idea is to conserve the physical conditions that contribute to high levels of biodiversity so that species and populations can find suitable areas in the future.[104]

Assessment of confidence based on evidence

Given the evidence and remaining uncertainties, there is **very high** confidence that ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society. The effectiveness of these actions is much less certain, however.

Climate Change Impacts in the United States

CHAPTER 9
HUMAN HEALTH

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9 HUMAN HEALTH

KEY MESSAGES

1. **Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.**
2. **Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.**
3. **Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.**
4. **Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.**

Climate change, together with other natural and human-made health stressors, influences human health and disease in numerous ways. Some existing health threats will intensify and new health threats will emerge. Not everyone is equally at risk. Important considerations include age, economic resources, and location. Preventive and adaptive actions, such as setting up extreme weather early warning systems and improving water infrastructure, can reduce the severity of these impacts, but there are limits to the effectiveness of such actions in the face of some projected climate change threats.

Climate change presents a global public health problem, with serious health impacts predicted to manifest in varying ways in different parts of the world. Public health in the U.S. can be affected by disruptions of physical, biological, and ecological systems, including disturbances originating in the U.S. and elsewhere. Health effects of these disruptions include increased respiratory and cardiovascular disease, injuries and premature deaths related to extreme weather events, changes in the prevalence and geographical distribution of food- and waterborne illnesses and other infectious diseases, and threats to mental health.

Key weather and climate drivers of health impacts include increasingly frequent, intense, and longer-lasting extreme heat, which worsens drought, wildfire, and air pollution risks; increasingly frequent extreme precipitation, intense storms, and changes in precipitation patterns that lead to drought and ecosystem changes (Ch. 2: Our Changing Climate); and rising sea levels that intensify coastal flooding and storm surge (Ch. 25: Coasts). Key drivers of vulnerability include the attributes of certain groups (age, socioeconomic status, race, current level of health – see Ch. 12: Indigenous Peoples for examples of health impacts on vulnerable populations) and of place (floodplains, coastal zones, and urban areas), as well as the resilience of critical public health infrastructure. Multi-stressor situations, such as impacts on vulnerable populations following natural disasters that also damage the social and physical infrastructure necessary for resilience and emergency response, are particularly important to consider when preparing for the impacts of climate change on human health.


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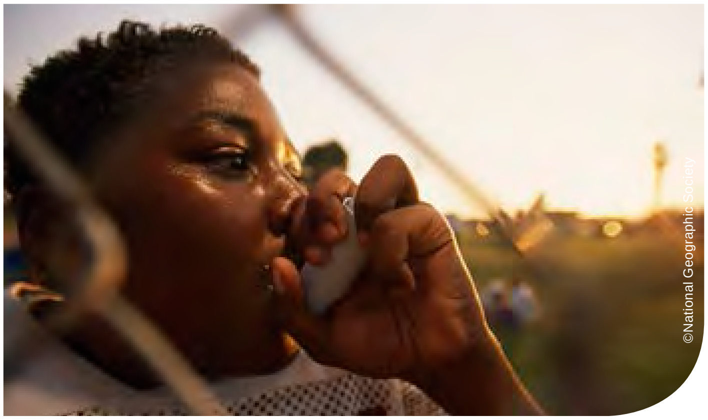
Key Message 1: Wide-ranging Health Impacts

Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.

Air Pollution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Climate change is projected to harm human health by increasing ground-level ozone and/or particulate matter air pollution in some locations. Ground-level ozone (a key component of smog) is associated with many health problems, such as diminished lung function, increased hospital admissions and emergency room visits for asthma, and increases in premature deaths.[1,2,3] Factors that affect ozone formation include heat, concentrations of precursor chemicals, and methane emissions, while particulate matter concentrations are affected by wildfire emissions and air stagnation episodes, among other factors.[4,5] By increasing these different factors, climate change is projected to lead to increased concentration of ozone and particulate matter in some regions.[6,7,8,9] Increases in global temperatures could cause associated increases in premature deaths related to worsened ozone and particle pollution. Estimates made assuming no change in regulatory controls or population characteristics have ranged from 1,000 to 4,300 additional premature deaths nationally per year by 2050 from combined ozone and particle health effects.[10,11] There is less certainty in the responses of airborne particles to climate change than there is about the response of ozone. Health-related costs of the current effects of ozone air pollution exceeding national standards have been estimated at $6.5 billion (in 2008 U.S. dollars) nationwide, based on a U.S. assessment of health impacts from ozone levels during 2000 to 2002.[12,13]

Climate Change Projected to Worsen Asthma

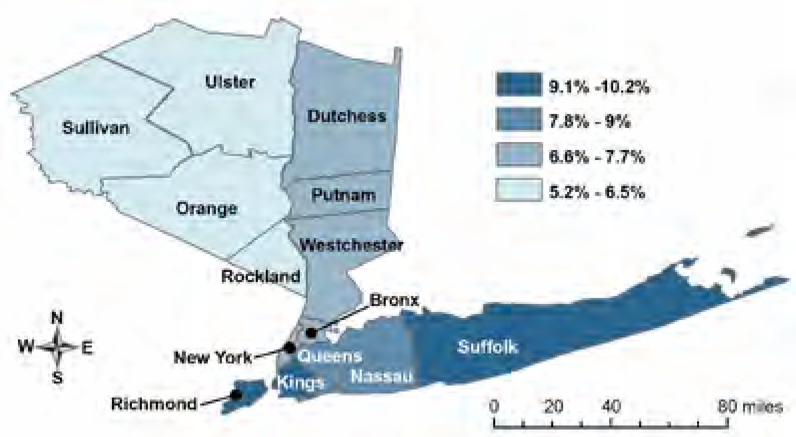

Figure 9.1. Projected increases in temperature, changes in wind patterns, and ecosystem changes will all affect future ground-level ozone concentrations. Climate projections using an increasing emissions scenario (A2) suggest that ozone concentrations in the New York metropolitan region will increase because of future climate change. This figure shows the estimated increase in ozone-related emergency room visits for children in New York in the 2020s (compared to the mid-1990s) resulting from climate change related increases in ozone concentrations. The results from this modeling exercise are shown as a percent change in visits specifically attributed to ozone exposure. For example, the 10.2% increase in Suffolk County represents five additional emergency room visits that could be attributed to increased ozone exposure over the baseline of 46 ozone-related visits from the mid-1990s. In 2010, an estimated 25.7 million Americans had asthma, which has become a problem in every state. (Figure source: Sheffield et al. 2011[14]).

Allergens

Climate change, resulting in more frost-free days and warmer seasonal air temperatures, can contribute to shifts in flowering time and pollen initiation from allergenic plant species, and increased CO_2 by itself can elevate production of plant-based allergens.[14,15,16,17,18,19] Higher pollen concentrations and longer pollen seasons can increase allergic sensitizations and asthma episodes,[20,21,22] and diminish productive work and school days.[19,22,23] Simultaneous exposure to toxic air pollutants can worsen allergic responses.[24,25,26] Extreme rainfall and rising temperatures can also foster indoor air quality problems, including the growth of indoor fungi and molds, with increases in respiratory and asthma-related conditions.[27] Asthma prevalence (the percentage of people who have ever been diagnosed with asthma and still have asthma) increased nationwide from 7.3% in 2001 to 8.4% in 2010. Asthma visits in primary care settings, emergency room visits, and hospitalizations were all stable from 2001 to 2009, and asthma death rates per 1,000 persons with asthma declined from 2001 to 2009.[28] To the extent that increased pollen exposures occur, patients and their physicians will face increased challenges in maintaining adequate asthma control.

Ragweed Pollen Season Lengthens

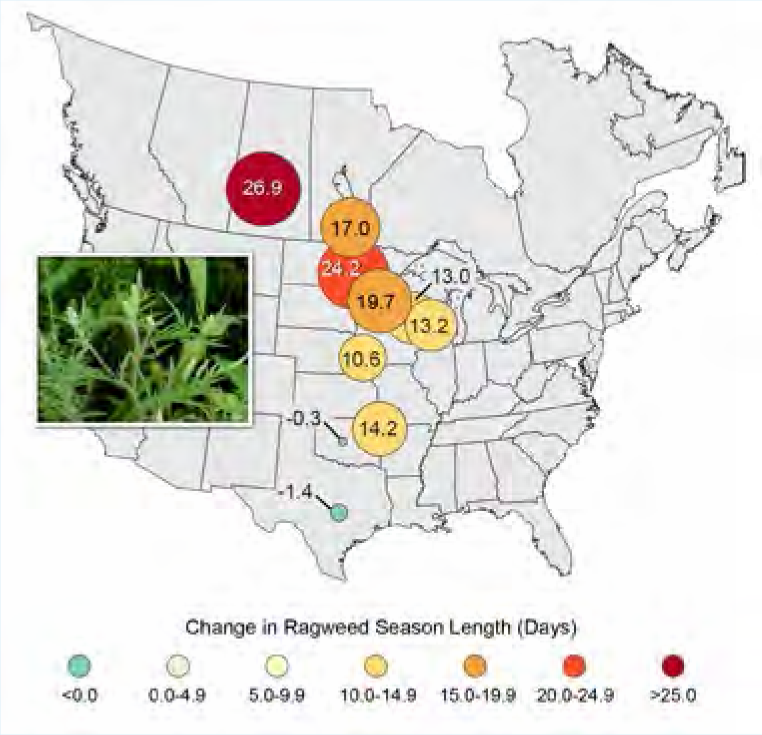

Figure 9.2. Ragweed pollen season length has increased in central North America between 1995 and 2011 by as much as 11 to 27 days in parts of the U.S. and Canada in response to rising temperatures. Increases in the length of this allergenic pollen season are correlated with increases in the number of days before the first frost. As shown in the figure, the largest increases have been observed in northern cities. (Data updated from Ziska et al. 2011[19]; Photo credit: Lewis Ziska, USDA).

Wildfires

Climate change is currently increasing the vulnerability of many forests to wildfire. Climate change is projected to increase the frequency of wildfire in certain regions of the United States (Ch. 7: Forests).[17,29] Long periods of record high temperatures are associated with droughts that contribute to dry conditions and drive wildfires in some areas.[30] Wildfire smoke contains particulate matter, carbon monoxide, nitrogen oxides, and various volatile organic compounds (which are ozone precursors)[31] and can significantly reduce air quality, both locally and in areas downwind of fires.[32,33] Smoke exposure increases respiratory and cardiovascular hospitalizations, emergency department visits, and medication dispensations for asthma, bronchitis, chest pain, chronic obstructive pulmonary disease (commonly known by its acronym, COPD), respiratory infections, and medical visits for lung illnesses.[32,34,35] It has been associated with hundreds of thousands of deaths annually, in an assessment of the global health risks from landscape fire smoke.[32,34,36,37] Future climate change is projected to increase wildfire risks and associated emissions, with harmful impacts on health.[17,38,39,40]

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Wildfire Smoke has Widespread Health Effects

Figure 9.3. Wildfires, which are projected to increase in some regions due to climate change, have health impacts that can extend hundreds of miles. Shown here, forest fires in Quebec, Canada, during July 2002 (red circles) resulted in up to a 30-fold increase in airborne fine particle concentrations in Baltimore, Maryland, a city nearly a thousand miles downwind. These fine particles, which are extremely harmful to human health, not only affect outdoor air quality, but also penetrate indoors, increasing the long-distance effects of fires on health.[41] An average of 6.4 million acres burned in U.S. wildfires each year between 2000 and 2010, with 9.5 and 9.1 million acres burned in 2006 and 2012, respectively.[42] Total global deaths from the effects of landscape fire smoke have been estimated at 260,000 to 600,000 annually between the years 1997 and 2006.[37] (Figure source: Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra satellite, Land Rapid Response Team, NASA/GSFC).

Temperature Extremes

Extreme heat events have long threatened public health in the United States.[43,44,45] Many cities, including St. Louis, Philadelphia, Chicago, and Cincinnati, have suffered dramatic increases in death rates during heat waves. Deaths result from heat stroke and related conditions,[44,45,46] but also from cardiovascular disease, respiratory disease, and cerebrovascular disease.[47,48] Heat waves are also associated with increased hospital admissions for cardiovascular, kidney, and respiratory disorders.[48,49,50] Extreme summer heat is increasing in the United States (Ch. 2: Our Changing Climate, Key Message 7),[51] and climate projections indicate that extreme heat events will be more frequent and intense in coming decades (Ch. 2: Our Changing Climate, Key Message 7).[2,52,53,54]

Some of the risks of heat-related sickness and death have diminished in recent decades, possibly due to better forecasting, heat-health early warning systems, and/or increased access to air conditioning for the U.S. population.[55] However, extreme heat events remain a cause of preventable death nationwide. Urban heat islands, combined with an aging population and increased urbanization, are projected to increase the vulnerability of urban populations to heat-related health impacts in the future (Ch. 11: Urban).[56,57,58]

Milder winters resulting from a warming climate can reduce illness, injuries, and deaths associated with cold and snow. Vulnerability to winter weather depends on many non-climate factors, including housing, age, and baseline health.[59] While deaths and injuries related to extreme cold events are projected to decline due to climate change, these reductions are not expected to compensate for the increase in heat-related deaths.[60,61]

Projected Temperature Change of Hottest Days

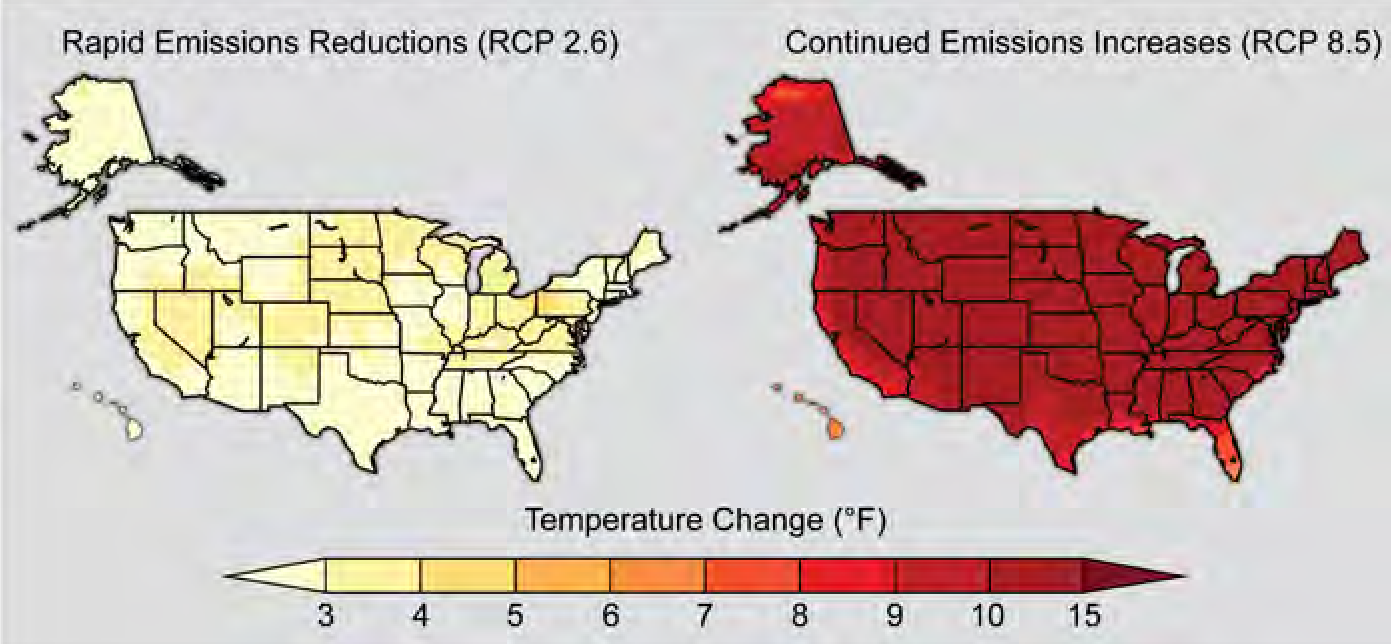

Figure 9.4. The maps show projected increases in the average temperature on the hottest days by late this century (2081-2100) relative to 1986-2005 under a scenario that assumes a rapid reduction in heat-trapping gases (RCP 2.6) and a scenario that assumes continued increases in these gases (RCP 8.5). The hottest days are those so hot they occur only once in 20 years. Across most of the continental United States, those days will be about 10ºF to 15ºF hotter in the future under the higher emissions scenario. (Figure source: NOAA NCDC / CICS-NC).

Precipitation Extremes: Heavy Rainfall, Flooding, and Droughts

The frequency of heavy precipitation events has already increased for the nation as a whole, and is projected to increase in all U.S. regions (Ch. 2: Our Changing Climate).[54,62] Increases in both extreme precipitation and total precipitation have contributed to increases in severe flooding events in certain regions (see Ch. 2: Our Changing Climate, Figure 2.21). Floods are the second deadliest of all weather-related hazards in the United States, accounting for approximately 98 deaths per year,[63] most due to drowning.[64] Flash floods (see Ch. 3: Water, "Flood Factors and Flood Types") and flooding associated with tropical storms result in the highest number of deaths.[63]

In addition to the immediate health hazards associated with extreme precipitation events when flooding occurs, other hazards can often appear once a storm event has passed. Elevated waterborne disease outbreaks have been reported in the weeks following heavy rainfall,[65] although other variables may affect these associations.[66] Water intrusion into buildings can result in mold contamination that manifests later, leading to indoor air quality problems. Buildings damaged during hurricanes are especially susceptible to water intrusion. Populations living in damp indoor environments experience increased prevalence of asthma and other upper respiratory tract symptoms, such as coughing and wheezing[67] as well as lower respiratory tract infections such as pneumonia, Respiratory Syncytial Virus (RSV), and RSV pneumonia (see Figure 9.7).[68]

At the opposite end of precipitation extremes, drought also poses risks to public health and safety.[69] Drought conditions may increase the environmental exposure to a broad set of health hazards including wildfires, dust storms, extreme heat events, flash flooding, degraded water quality, and reduced water quantity. Dust storms associated with drought conditions contribute to degraded air quality due to particulates and have been associated with increased incidence of Coccidioidomycosis (Valley fever), a fungal pathogen, in Arizona and California.[70]

Disease Carried by Vectors

Climate is one of the factors that influence the distribution of diseases borne by vectors (such as fleas, ticks, and mosquitoes, which spread pathogens that cause illness).[71,72,73,74,75,76,77,78] The geographic and seasonal distribution of vector populations, and the diseases they can carry, depend not only on climate but also on land use, socioeconomic and cultural factors, pest control, access to health care, and human responses to disease risk, among other factors.[72,73,79,80,81] Daily, seasonal, or year-to-year climate variability can sometimes result in vector/pathogen adaptation and shifts or expansions in their geographic ranges.[73,74,81] Such shifts can alter disease incidence depending on vector-host interaction, host immunity, and pathogen evolution.[71] North Americans are currently at risk from numerous vector-borne diseases, including Lyme,[75,82,83,84] dengue fever,[85] West Nile virus,[86] Rocky Mountain spotted fever,[87] plague, and tularemia.[88] Vector-borne pathogens not currently found in the United States, such as chikungunya, Chagas disease, and Rift Valley fever viruses, are also threats. Climate change effects on the geographical distribution and incidence of vector-borne diseases in other countries where these diseases are already found can also affect North Americans, especially as a result of increasing trade with, and travel to, tropical and subtropical areas.[74,81] Whether climate change in the U.S. will increase the chances of domestically acquiring diseases such as dengue fever is uncertain, due to vector-control efforts and lifestyle factors, such as time spent indoors, that reduce human-insect contact.

Infectious disease transmission is sensitive to local, small-scale differences in weather, human modification of the landscape, the diversity of animal hosts,[83] and human behavior that affects vector-human contact, among other factors. There is a need for finer-scale, long-term studies to help quantify the relationships among weather variables, vector range, and vector-borne pathogen occurrence, the consequences of shifting distributions of vectors and pathogens, and the impacts on human behavior. Enhanced vector surveillance and human disease tracking are needed to address these concerns.


James Gathany, CDC

The *Culex tarsalis* mosquito is a vector that transmits West Nile Virus.

TRANSMISSION CYCLE OF LYME DISEASE

The development and survival of blacklegged ticks, their animal hosts, and the Lyme disease bacterium, *Borrelia burgdorferi*, are strongly influenced by climatic factors, especially temperature, precipitation, and humidity. Potential impacts of climate change on the transmission of Lyme disease include: 1) changes in the geographic distribution of the disease due to the increase in favorable habitat for ticks to survive off their hosts;[89] 2) a lengthened transmission season due to earlier onset of higher temperatures in the spring and later onset of cold and frost; 3) higher tick densities leading to greater risk in areas where the disease is currently observed, due to milder winters and potentially larger rodent host populations; and 4) changes in human behaviors, including increased time outdoors, which may increase the risk of exposure to infected ticks.

Projected Changes in Tick Habitat

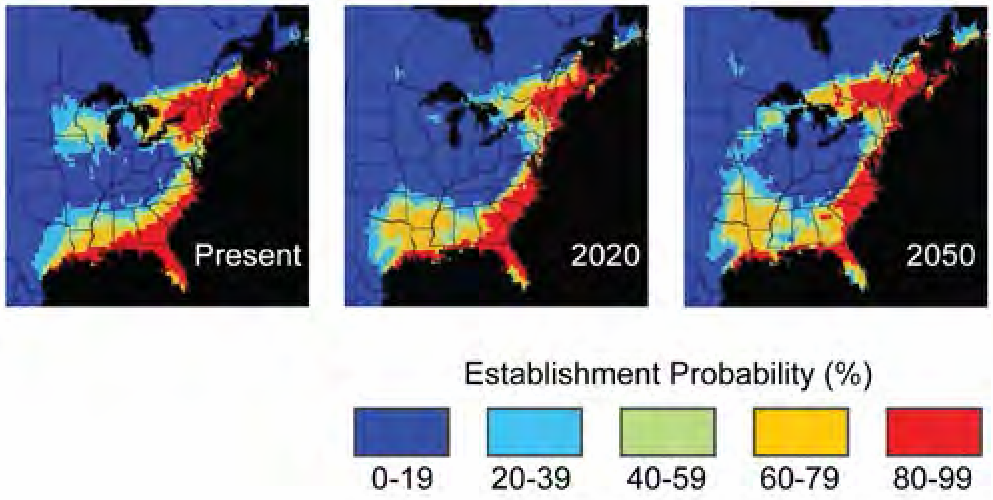

Figure 9.5. The maps show the current and projected probability of establishment of tick populations (*Ixodes scapularis*) that transmit Lyme disease. Projections are shown for 2020, 2050, and 2080. The projected expansion of tick habitat includes much of the eastern half of the country by 2080. For some areas around the Gulf Coast, the probability of tick population establishment is projected to decrease by 2080. (Figure source: adapted from Brownstein et al. 2005[90]).

Food- and Waterborne Diarrheal Disease

Diarrheal disease is a major public health issue in developing countries and, while not generally increasing in the United States, remains a persistent concern nonetheless. Exposure to a variety of pathogens in water and food causes diarrheal disease. Air and water temperatures, precipitation patterns, extreme rainfall events, and seasonal variations are all known to affect disease transmission.[65,91,92] In the United States, children and the elderly are most vulnerable to serious outcomes, and those exposed to inadequately or untreated groundwater will be among those most affected.

In general, diarrheal diseases including Salmonellosis and Campylobacteriosis are more common when temperatures are higher,[93,94] though patterns differ by place and pathogen. Diarrheal diseases have also been found to occur more frequently in conjunction with both unusually high and low precipitation.[95] Sporadic increases in streamflow rates, often preceded by rapid snowmelt[96] and changes in water treatment,[97] have also been shown to precede outbreaks. Risks of waterborne illness and beach closures resulting from changes in the magnitude of recent precipitation (within the past 24 hours) and in lake temperature are expected to increase in the Great Lakes region due to projected climate change.[98,99]

Projected Change in Heavy Precipitation Events

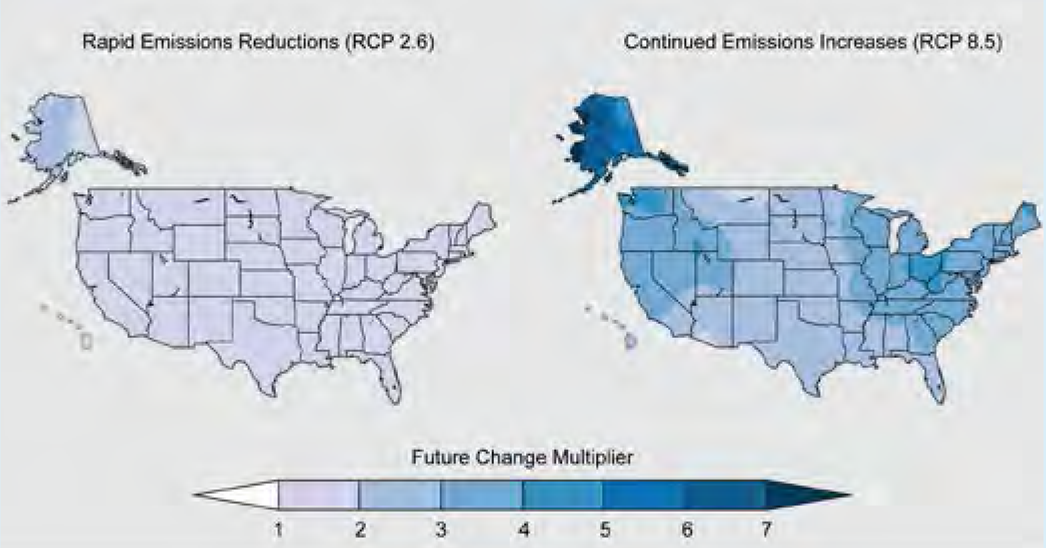

Figure 9.6. Maps show the increase in frequency of extreme daily precipitation events (a daily amount that now occurs just once in 20 years) by the later part of this century (2081-2100) compared to the latter part of the last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the United States. Under a rapid emissions reduction scenario (RCP 2.6), these events would occur nearly twice as often. For a scenario assuming continued increases in emissions (RCP 8.5), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC).

Heavy Downpours are Increasing Exposure to Disease

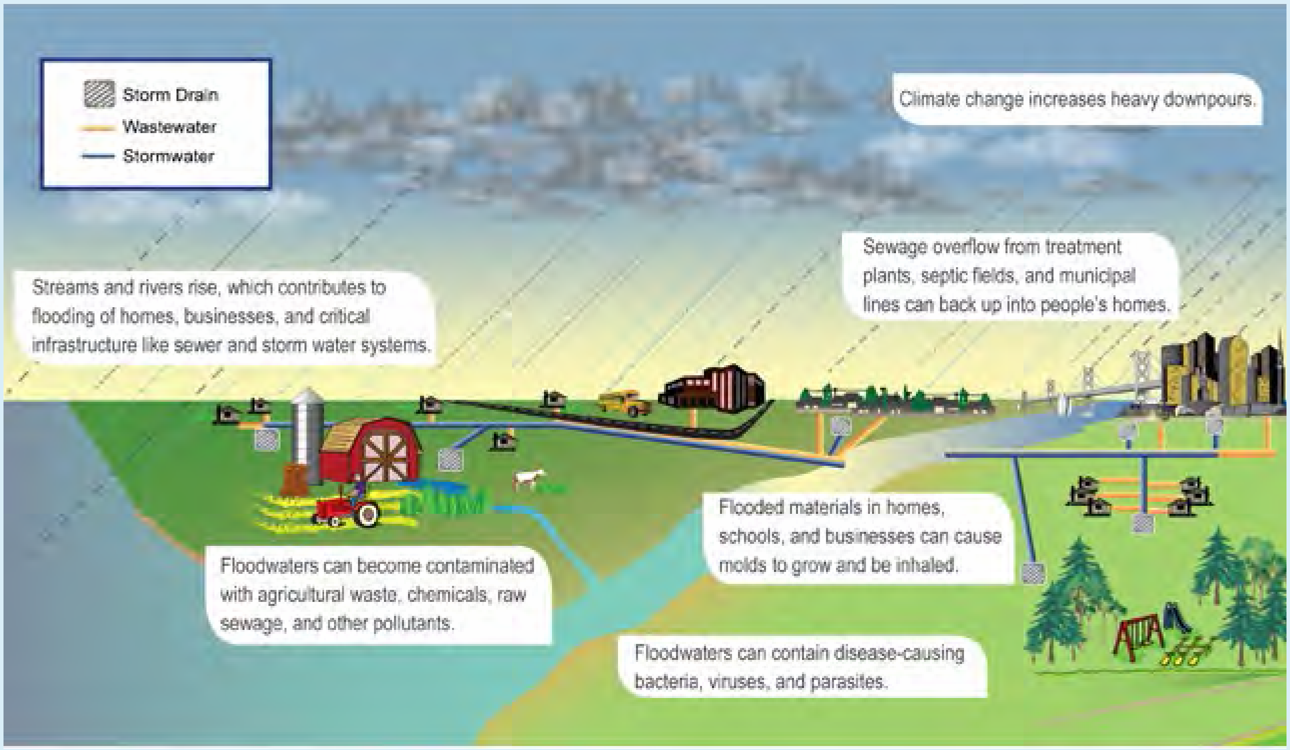

Figure 9.7. Heavy downpours, which are increasing in the United States, have contributed to increases in heavy flood events (Ch. 2: Our Changing Climate, Key Message 6). The figure above illustrates how people can become exposed to waterborne diseases. Human exposures to waterborne diseases can occur via drinking water, as well as recreational waters.[100,101,102,103] (Figure source: NOAA NCDC / CICS-NC).

Harmful Bloom of Algae

Figure 9.8. Remote sensing color image of harmful algal bloom in Lake Erie on October 9, 2011. The bright green areas have high concentrations of algae, which can be harmful to human health. The frequency and range of harmful blooms of algae are increasing.[102,103] Because algal blooms are closely related to climate factors, projected changes in climate could affect algal blooms and lead to increases in water- and food-borne exposures and subsequent cases of illness.[103] Other factors related to increases in harmful algal blooms include shifts in ocean conditions such as excess nutrient inputs.[101,102,103] (Figure source: NASA Earth Observatory[104]).

Food Security

Globally, climate change is expected to threaten food production and certain aspects of food quality, as well as food prices and distribution systems. Many crop yields are predicted to decline due to the combined effects of changes in rainfall, severe weather events, and increasing competition from weeds and pests on crop plants (Ch. 6: Agriculture, Key Message 6).[105,106] Livestock and fish production is also projected to decline.[107] Prices are expected to rise in response to declining food production and associated trends such as increasingly expensive petroleum (used for agricultural inputs such as pesticides and fertilizers).[108]

While the U.S. will be less affected than some other countries,[109,110] the nation will not be immune. Health can be affected in several ways. First, Americans with particular dietary patterns, such as Alaska Natives, will confront shortages of key foods (Ch. 12: Indigenous Peoples, Key Message 1).[111] Second, food insecurity increases with rising food prices.[112] In such situations, people cope by turning to nutrient-poor but calorie-rich foods, and/or they endure hunger, with consequences ranging from micronutrient malnutrition to obesity.[113] Third, the nutritional value of some foods is projected to decline. Elevated atmospheric CO_2 is associated with decreased plant nitrogen concentration, and therefore decreased protein, in many crops, such as barley, sorghum, and soy.[114] The nutrient content of crops is also projected to decline if soil nitrogen levels are suboptimal, with reduced levels of nutrients such as calcium, iron, zinc, vitamins, and sugars, although this effect is alleviated if sufficient nitrogen is supplied.[115] Fourth, farmers are expected to need to use more herbicides and pesticides because of increased growth of pests[116] and weeds[117] as well as decreased effectiveness[118] and duration[119] of some of these chemicals (Ch. 6: Agriculture). Farmers, farmworkers, and consumers will thus sustain increased exposure to these substances and their residues, which can be toxic. These climate change impacts on the nutritional value of food exist within a larger context in which other factors, such as agricultural practices, food distribution systems, and consumer food choices, also play key roles. Adaptation activities can reduce the health-related impacts of some of the anticipated food security challenges (Ch. 6: Agriculture).

Mental Health and Stress-related Disorders

Mental illness is one of the major causes of suffering in the United States, and extreme weather events can affect mental health in several ways.[120,121,122,123] First, following disasters, mental health problems increase, both among people with no history of mental illness, and those at risk – a phenomenon known as “common reactions to abnormal events.” These reactions may be short-lived or, in some cases, long-lasting.[124] For example, research demonstrated high levels of anxiety and post-traumatic stress disorder among people affected by Hurricane Katrina,[125] and similar observations have followed floods[126] and heat waves.[127] Some evidence suggests wildfires have similar effects.[128] All of these events are increasingly fueled by climate change (see Ch. 2: Our Changing Climate). Other health consequences of intensely stressful exposures are also a concern, such as adverse birth outcomes including pre-term birth, low birth weight, and maternal complications.[129]

Second, some patients with mental illness are especially susceptible to heat.[130] Suicide rates vary with weather,[131] rising with high temperatures,[132] suggesting potential climate change impacts on depression and other mental illnesses. Dementia is a risk factor for hospitalization and death during heat waves.[127,133] Patients with severe mental illness such as schizophrenia are at risk during hot weather because their medications may interfere with temperature regulation or even directly cause hyperthermia.[134] Additional potential mental health impacts, less well understood, include the possible distress associated with environmental degradation[135] and displacement,[136] and the anxiety and despair that knowledge of climate change might elicit in some people (Ch. 12: Indigenous Peoples, Key Message 5).[122]

Key Message 2: Most Vulnerable at Most Risk

Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.

Climate change will increase the risk of climate-related illness and death for a number of vulnerable groups in the United States, as when Hurricane Katrina devastated New Orleans in 2005. Children, primarily because of physiological and developmental factors, will disproportionately suffer from the effects of heat waves,[47] air pollution, infectious illness, and trauma resulting from extreme weather events.[14,16,18,22,138,139,140,141]

The country’s older population also could be harmed more as the climate changes. Older people are at much higher risk of dying during extreme heat events.[45,47,139,142] Pre-existing health conditions also make older adults susceptible to cardiac and respiratory impacts of air pollution[26] and to more severe consequences from infectious diseases;[143] limited mobility among older adults can also increase flood-related health risks.[144] Limited resources and an already high burden of chronic health conditions, including heart disease, obesity, and diabetes, will place the poor at higher risk of health impacts from climate change than higher income groups.[26,47] Potential increases in food cost and limited availability of some foods will exacerbate current dietary inequalities and have significant health ramifications for the poorer segments of our population (Ch. 12: Indigenous Peoples, Key Message 1).[110,145]

Climate change will disproportionately affect low-income communities and some communities of color (Ch. 12: Indigenous Peoples, Key Message 2),[139,149,151,152,153,154,155,156,157] raising environmental justice concerns. Existing health disparities[153,158,159] and other inequities[160,161] increase vulnerability. Climate change related issues that have an equity component include heat waves, air quality, and extreme weather and climate events. For example, Hurricane Katrina demonstrated how vulnerable certain groups of people were to extreme weather events, because many low-income and of-color New Orleans residents were killed, injured, or had difficulty evacuating and recovering from the storm.[154,155,156,161,162,163,164]

Elements of Vulnerability to Climate Change

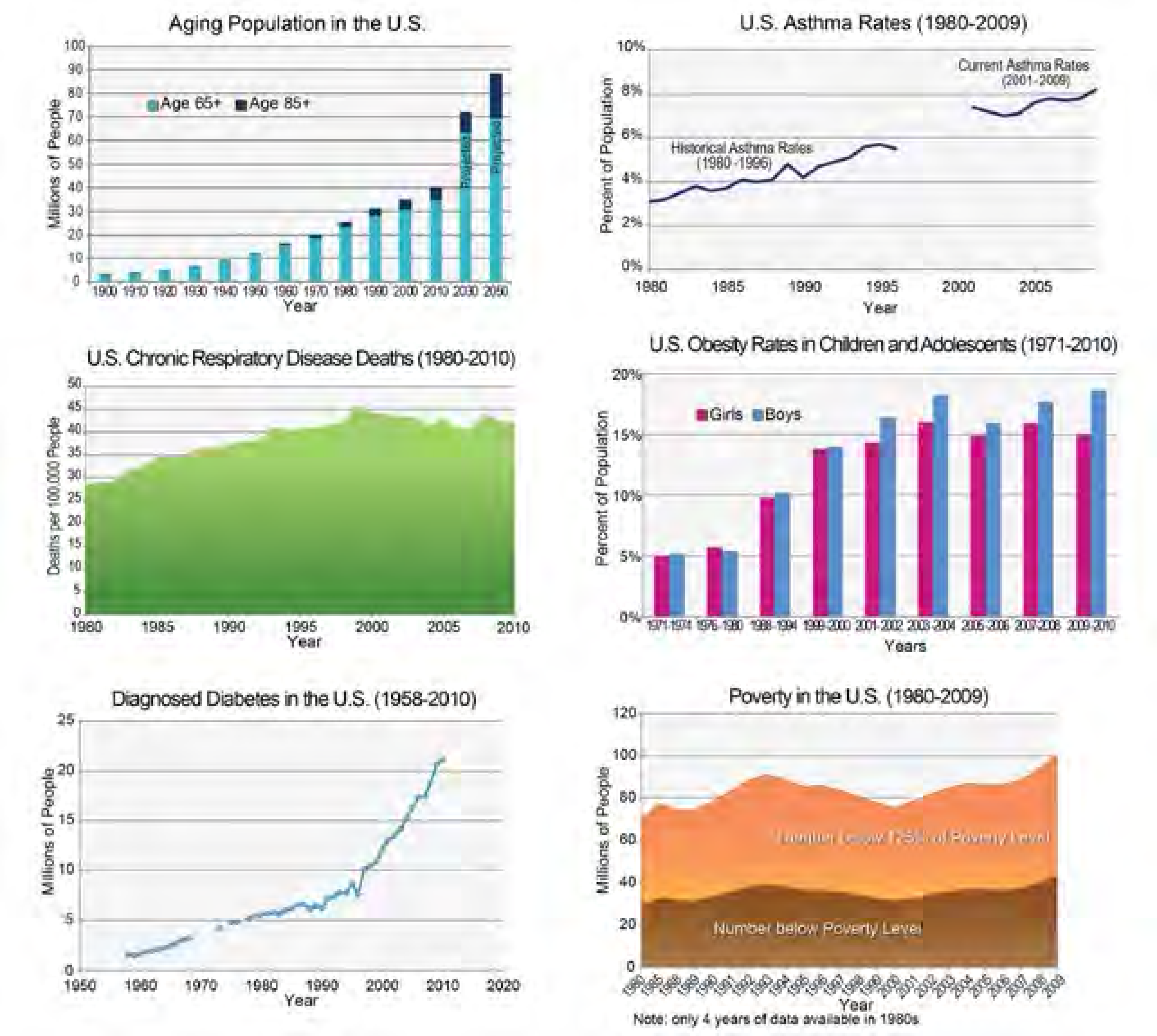

Figure 9.9. A variety of factors can increase the vulnerability of a specific demographic group to health effects due to climate change. For example, older adults are more vulnerable to heat stress because their bodies are less able to regulate their temperature. Overall population growth is projected to continue to at least 2050, with older adults comprising an increasing proportion of the population. Similarly, there are an increasing number of people who are obese and have diabetes, heart disease, or asthma, which makes them more vulnerable to a range of climate-related health impacts. Their numbers are also rising. The poor are less able to afford the kinds of measures that can protect them from and treat them for various health impacts. (Data from CDC; Health E-Stat; U.S. Census Bureau 2010, 2012; and Akinbami et al. 2011[137]).

SOCIETAL SYSTEM FAILURES DURING EXTREME EVENTS

We have already seen multiple system failures during an extreme weather event in the United States, as when Hurricane Katrina struck New Orleans.[146] Infrastructure and evacuation failures and collapse of critical response services during a storm is one example of multiple system failures. Another example is a loss of electrical power during a heat wave or wildfires, which can reduce food and water safety.[147] Air conditioning has helped reduce illness and death due to extreme heat,[148] but if power is lost, everyone is vulnerable. By their nature, such events can exceed our capacity to respond.[79] In succession, these events severely deplete our resources needed to respond, from the individual to the national scale, but disproportionately affect the most vulnerable populations.[149]

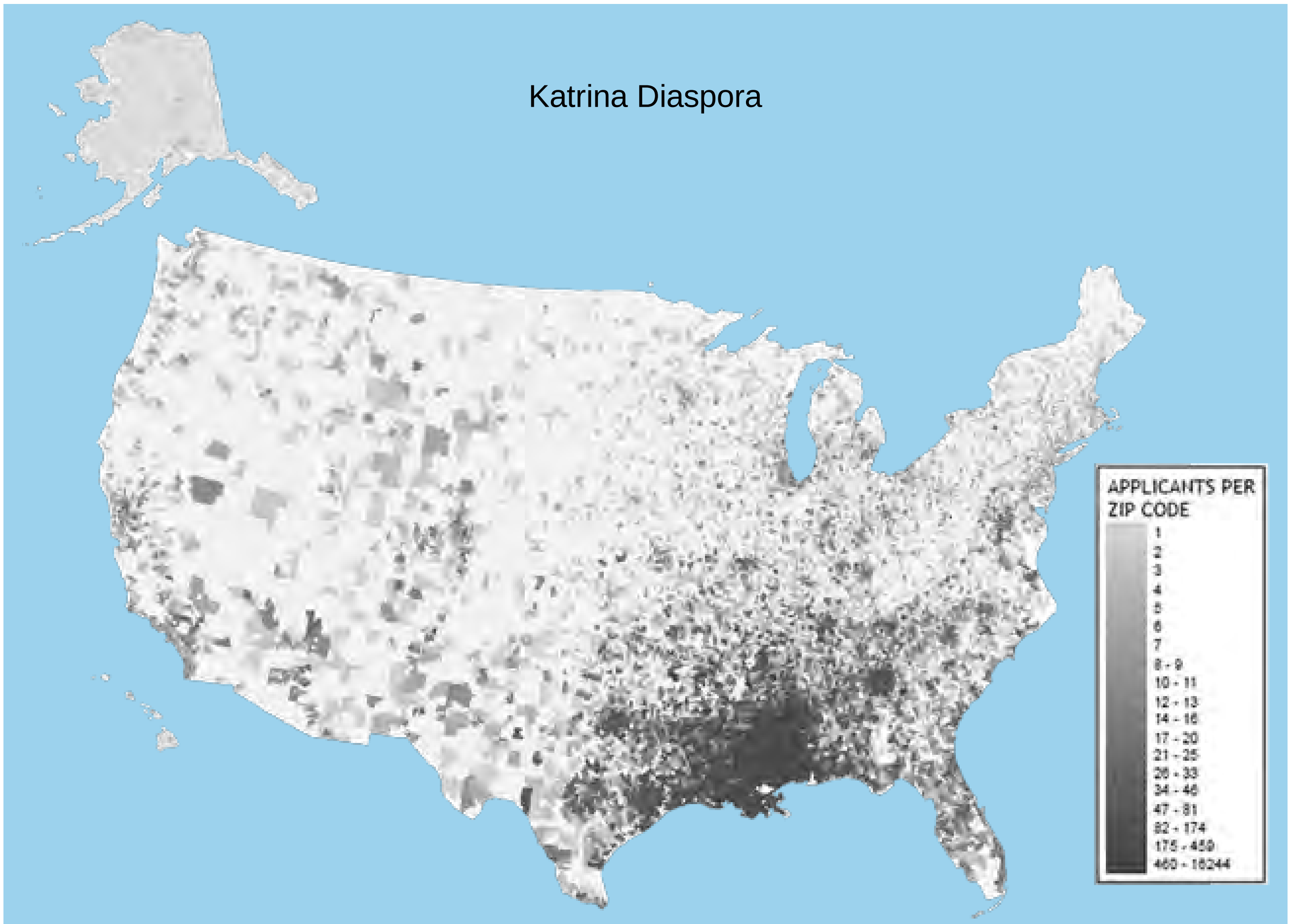

Figure 9.10. This map illustrates the national scope of the dispersion of displaced people from Hurricane Katrina. It shows the location by zip code of the 800,000 displaced Louisiana residents who requested federal emergency assistance. The evacuees ended up dispersed across the entire nation, illustrating the wide-ranging impacts that can flow from extreme weather events, such as those that are projected to increase in frequency and/or intensity as climate continues to change (Ch. 2: Our Changing Climate, Key Message 8). (Figure source: Kent 2006[150]).

MULTIPLE CLIMATE STRESSORS AND HEALTH

Climate change impacts add to the *cumulative* stresses currently faced by vulnerable populations including children, the elderly, the poor, some communities of color, and people with chronic illnesses. These populations, and others living in certain places such as cities, floodplains, and coastlines, are more vulnerable not only to extreme events but also to ongoing, persistent climate-related threats. These threats include poor air quality, heat, drought, flooding, and mental health stress. Over time, the accumulation of these stresses will be increasingly harmful to these populations.

Key Message 3: Prevention Provides Protection

Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.

Prevention is a central tenet of public health. Many conditions that are difficult and costly to treat when a patient gets to the doctor could be prevented before they occur at a fraction of the cost. Similarly, many of the larger health impacts associated with climate change can be prevented through early action at significantly lower cost than dealing with them after they occur.[153,165] Early preventive interventions, such as early warnings for extreme weather, can be particularly cost-effective.[166,167,168] As with many illnesses,[169] once impacts are apparent, even the best adaptive efforts can be overwhelmed, and damage control becomes the priority.[62]

Activities that reduce carbon pollution often also provide co-benefits in the form of preventive health measures. For example, reliance on cleaner energy sources for electricity production[174] and more efficient and active transport, like biking or walking,[175] can have immediate public health benefits, through improved air quality and lowered rates of obesity, diabetes, and heart disease.[176] Reducing carbon pollution also reduces long-term adverse climate-health impacts, thus producing cost savings in the near and longer term.[176] Preventing exposures to other climate-sensitive impacts already apparent can similarly result in cost savings. For instance, heat wave early warning systems protect vulnerable groups very effectively and are much less expensive than treating and coping with heat illnesses. Systems that monitor for early outbreaks of disease are also typically much less expensive than treating communities once outbreaks take hold.[12,49,177]

Effective communication is a fundamental part of prevention. The public must understand risk in order to endorse proactive risk management. The public is familiar with the health risks of smoking, but not so for climate change. When asked about climate change impacts, Americans do not mention health impacts,[178] and when asked about health impacts specifically, most believe it will affect people in a different time or place.[179] But diverse groups of Americans find information on health impacts to be helpful once received, particularly information about the health benefits of mitigation (reducing carbon emissions) and adaptation.[180]

Determining which types of prevention to invest in (such as monitoring, early warning systems, and land-use changes that reduce the impact of heat and floods) depends on several factors, including health problems common to that particular area, vulnerable populations, the preventive health systems already in place, and the expected impacts of climate change.[181] Local capacity to adapt is very important; unfortunately the most vulnerable populations also frequently have limited resources for managing climate-health risks.

Overall, the capacity of the American public health and health care delivery systems faces many challenges.[182] The cost of dealing with current health problems is diverting resources from preventing them in the first place. This makes the U.S. population more vulnerable.[183,184] Without careful consideration of how to prevent future impacts, similar patterns could emerge regarding the health impacts from climate change. However, efforts to quantify and map vulnerability factors at the community level are underway.[151,164,185]

There are public health programs in some locations that address climate-sensitive health issues, and integrating such programs into the mainstream public health toolkit as adaptation needs increase would improve public health resilience to climate change.[79,186,187] Given that these programs have demonstrated efficacy against current threats that are expected to worsen with climate change, it is prudent to invest in creating

LARGE-SCALE ENVIRONMENTAL CHANGE FAVORS DISEASE EMERGENCE

Climate change is causing large-scale changes in the environment, increasing the likelihood of the emergence or reemergence of unfamiliar disease threats.[170] Factors include shifting ranges of disease-carrying pests, lack of immunity and preparedness, inadequate disease monitoring, and increasing global travel. Diseases including Lyme disease and dengue fever pose increasing health threats to the U.S. population; the number of U.S. patients hospitalized with dengue fever more than tripled from 2000 to 2007.[171] Although most cases of dengue fever during that time period were acquired outside the contiguous United States, the introduction of infected people into areas where the dengue virus vector is established increases the risk of locally acquired cases. The public health system is not fully prepared to monitor or respond to these growing disease risks. The introduction of new diseases into non-immune populations has been and continues to be a major challenge in public health. There are concerns that climate change may provide opportunities for pathogens to expand or shift their geographic ranges.[172,173]

the strongest climate-health preparedness programs possible.[153] One survey highlighted opportunities to address climate change preparedness activities and climate-health research[181] before needs become more widespread. *America's Climate Choices: Adapting to the Impacts of Climate Choices* (Table 3.5) provides examples of health adaptation options.[187]

Key Message 4: Responses Have Multiple Benefits

Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.

Policies and other strategies intended to reduce carbon pollution and mitigate climate change can often have independent influences on human health. For example, reducing CO_2 emissions through renewable electrical power generation can reduce air pollutants like particles and sulfur dioxide. Efforts to improve the resiliency of communities and human infrastructure to climate change impacts can also improve human health. There is a growing recognition that the magnitude of health "co-benefits," like reducing both pollution and cardiovascular disease, could be significant, both from a public health and an economic standpoint.[176,188,189] Some climate change resilience efforts will benefit health, but potential co-harms should be considered when implementing these strategies. For example, although there are numerous benefits to urban greening, such as reducing the urban heat island effect while simultaneously promoting an active healthy lifestyle,[159,190,191] the urban planting of certain allergenic pollen producing species[22] could increase human pollen exposure and allergic illness. Increased pollen exposure has been linked to increased emergency department visits related to asthma and wheezing[192] in addition to respiratory allergic illnesses such as allergic rhinitis or hay fever.[193] The selective use of low to moderate pollen-producing species can decrease pollen exposure.[194]

Much of the focus of health co-benefits has been on reducing health-harming air pollution.[6,174,175,195,196] One study projects that replacing 50% of short motor vehicle trips with bicycle use and the other 50% with other forms of transportation like walking or public transit would avoid nearly 1,300 deaths in 11 midwestern metropolitan areas and create up to $8 billion in health benefits annually for the upper Midwest region.[188] Such multiple-benefit actions can reduce heat-trapping gas emissions that lead to climate change, improve air quality by reducing vehicle pollutant emissions, and improve fitness and health through increased physical activity.[99,197,198,199,200]

Innovative urban design could create increased access to active transport.[99] The compact geographical area found in cities presents opportunities to reduce energy use and emissions of heat-trapping gases and other air pollutants through active transit, improved building construction, provision of services, and infrastructure creation, such as bike paths and sidewalks.[197,201] Urban planning strategies designed to reduce the urban heat island effect, such as green/cool roofs, increased green space, parkland and urban canopy, could reduce indoor temperatures, improve indoor air quality, and could produce additional societal co-benefits by promoting social interaction and prioritizing vulnerable urban populations.[191,197]

Patterns of change related to improving health can also have co-benefits in terms of reducing carbon pollution and mitigating climate change. Current U.S. dietary guidelines and many health professionals have recommended diets higher in fruits and vegetables and lower in red meat as a means of helping

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to reduce the risk of cardiovascular disease and some cancers.[199,202,203] These changes in food consumption, and related changes to food production, could have co-benefits in terms of reducing greenhouse gas emissions. While the greenhouse gas footprint of the production of other foods, compared to sources such as livestock, is highly dependent on a number of factors, production of livestock currently accounts for about 30% of the U.S. total emissions of methane.[199,203,204] This amount of methane can be reduced somewhat by recovery methods such as the use of biogas digesters, but future changes in dietary practices, including those motivated by considerations other than climate change mitigation, could also have an effect on the amount of methane emitted to the atmosphere.[205]

In addition to producing health co-benefits,[206] climate change prevention and preparedness measures could also yield positive equity impacts. For example, several studies have found that communities of color and poor communities experience disproportionately high exposures to air pollution.[207,208] Climate change mitigation policies that improve local air quality thus have the potential to strongly benefit health in these communities.

An area where adaptation policy could produce more equitable health outcomes is with respect to extreme weather events. As discussed earlier, Hurricane Katrina demonstrated that communities of color, poor communities, and certain other vulnerable populations (like new immigrant communities) are at a higher risk to the adverse effects of extreme weather events.[152,155] These vulnerable populations could benefit from urban planning policies that ensure that new buildings, including homes, are constructed to resist extreme weather events.[197]

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PHOTO CREDITS

Introduction to chapter; tourists walking close to misters keeping cool during heat wave in Las Vegas, Nevada, as shown in top banner: ©Julie Jacobson/AP/Corbis

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages were developed during technical discussions and expert deliberation at a two-day meeting of the eight chapter Lead Authors, plus Susan Hassol and Daniel Glick, held in Boulder, Colorado May 8-9, 2012; through multiple technical discussions via six teleconferences from January through June 2012, and an author team call to finalize the Traceable Account draft language on Oct 12, 2012; and through other various communications on points of detail and issues of expert judgment in the interim. The author team also engaged in targeted consultations during multiple exchanges with Contributing Authors, who provided additional expertise on subsets of the key message. These discussions were held after a review of the technical inputs and associated literature pertaining to human health, including a literature review,[209] workshop reports for the Northwest and Southeast United States, and additional technical inputs on a variety of topics.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and diseases-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast United States. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

Air Pollution:

The effects of decreased ozone air quality on human health have been well documented concerning projected increases in ozone,[6,7,9,11,39] even with uncertainties in projections owing to the complex formation chemistry of ozone and climate change, precursor chemical inventories, wildfire emission, stagnation episodes, methane emissions, regulatory controls, and population characteristics.[4] Ozone exposure leads to a number of health impacts.[1,2]

Allergens:

The effects of increased temperatures and atmospheric CO_2 concentration have been documented concerning shifts in flowering time and pollen initiation from allergenic plants, elevated production of plant-based allergens, and health effects of increased pollen concentrations and longer pollen seasons.[15,16,17,18,20,22,23,24,26,106] Additional studies have shown extreme rainfall and higher temperatures can lead to increased indoor air quality issues such as fungi and mold health concerns.[27]

Wildfire:

The effects of wildfire on human health have been well documented with increase in wildfire frequency[17,29,39,40] leading to decreased air quality[31,32,33] and negative health impacts.[32,34,36]

Temperature Extremes:

The effects of temperature extremes on human health have been well documented for increased heat waves,[51,53,54] which cause more deaths,[47,48] hospital admissions[50] and population vulnerability.[56,57]

Precipitation Extremes - Heavy Rainfall, Flooding, and Droughts:

The effects of weather extremes on human health have been well documented, particularly for increased heavy precipitation, which has contributed to increases in severe flooding events in certain regions. Floods are the second deadliest of all weather-related hazards in the United States.[63,64] Elevated waterborne disease outbreaks have been reported in the weeks following heavy rainfall,[65] although other variables may affect these associations.[66] Populations living in damp indoor environments experience increased prevalence of asthma and other upper respiratory tract symptoms.[67]

Disease Carried by Vectors:

Climate is one of the factors that influence the range of disease vectors; [73,74,76] a shift in the current range may increase interactions with people and affect human health.[71] North Americans are currently at risk from a number of vector-borne diseases.[75,82,83,85,86,87] There are some ambiguities on the relative role and contribution of climate change among the range of factors that affect disease transmission dynamics.[71,72,73,74,75,76] However, observational studies are already underway and confidence is high based on scientific literature that climate change has contributed to the expanded range of certain disease vectors, including *Ixodes* ticks which are vectors for Lyme disease in the United States.[78,84,89]

Food- and Waterborne Diarrheal Disease:
There has been extensive research concerning the effects of climate change on water- and food-borne disease transmission.[92,93,95,96,97] The current evidence base strongly supports waterborne diarrheal disease being both seasonal and sensitive to climate variability. There are also multiple studies associating extreme precipitation events with waterborne disease outbreaks.[65] This evidence of responsiveness of waterborne disease to weather and climate, combined with evidence strongly suggesting that temperatures will increase and extreme precipitation events will increase in frequency and severity (Ch. 2: Our Changing Climate), provides a strong argument for climate change impacts on waterborne disease by analogy. There are multiple studies associating extreme precipitation events with waterborne disease outbreaks and strong climatological evidence for increasing frequency and intensity of extreme precipitation events in the future. The scientific literature modeling the projected impacts of climate change on waterborne disease is somewhat limited, however. Combined, we therefore have overall medium confidence in the impact of climate change on waterborne and food-borne disease.

Harmful Algal Blooms:
Because algal blooms are closely related to climate factors, projected changes in climate could affect algal blooms and lead to increases in food- and waterborne exposures and subsequent cases of illness.[96,97,98,99,103] Harmful algal blooms have multiple exposure routes.[100]

Food Security:
Climate change is expected to have global impacts on both food production and certain aspects of food quality. The impact of temperature extremes, changes in precipitation and elevated atmospheric CO_2, and increasing competition from weeds and pests on crop plants are areas of active research (Ch. 6: Agriculture, Key Message 6).[105,106] The U.S. as a whole will be less affected than some other countries. However, the most vulnerable, including those dependent on subsistence lifestyles, especially Alaska Natives and low-income populations, will confront shortages of key foods.

Mental Health and Stress-Related Disorders:
The effects of extreme weather on mental health have been extensively studied.[120,122,123] Studies have shown the impacts of mental health problems after disasters,[124] with extreme events like Hurricane Katrina,[125] floods,[126] heat waves,[127] and wildfires[128] having led to mental health problems. Further work has shown that some people with mental illnesses are especially vulnerable to heat. Suicide rates vary with weather,[131,132] dementia is a risk factor for hospitalization and death during heat waves,[127,133] and medications for schizophrenia may interfere with temperature regulation or even directly cause hyperthermia.[134] Additional potential mental health impacts include distress associated with environmental degradation, displacement, and the knowledge of climate change.[122,123,136]

New information and remaining uncertainties
Important new evidence on heat-health effects[44,45] confirmed many of the findings from a prior literature review. Uncertainties in the magnitude of projections of future climate-related morbidity and mortality can result from differences in climate model projections of the frequency and intensity of extreme weather events such as heat waves and other climate parameters such as precipitation.

Efforts to improve the information base should address the coordinated monitoring of climate and improved surveillance of health effects.

Assessment of confidence based on evidence
Overall: **Very High** confidence. There is considerable consensus and a high quality of evidence in the published peer-reviewed literature that a wide range of health effects will be exacerbated by climate change in the United States. There is less agreement on the magnitude of these effects because of the exposures in question and the multi-factorial nature of climate-health vulnerability, with regional and local differences in underlying health susceptibilities and adaptive capacity. Other uncertainties include how much effort and resources will be put into improving the adap-

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

tive capacity of public health systems to prepare in advance for the health effects of climate change, prevent harm to individual and community health, and limit associated health burdens and societal costs.

Increased Ozone Exposure: **Very High** confidence.
Allergens: **High** confidence.
Wildfires: **Very High** confidence.
Thermal Extremes: **Very High** confidence.
Extreme Weather Events: **Very High** confidence.
Vector-borne Infectious Diseases: **High** or **Very High** confidence for shift in range of disease-carrying vectors. **Medium** confidence for whether human disease transmission will follow.
Food- and Waterborne disease: **Medium** confidence.
Harmful Algal Blooms: **Medium** confidence.
Food Security: **Medium** confidence for food quality; **High** confidence for food security.

Threats to Mental Health: **Very High** confidence for post-disaster impacts; **Medium** confidence for climate-induced stress.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast regions.[210] Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

Current epidemiological evidence on climate-sensitive health outcomes in the U.S. indicates that health impacts will differ substantially by location, pathway of exposure, underlying susceptibility, and adaptive capacity. These disparities in health impacts will largely result from differences in the distribution of individual attributes in a population that confers vulnerability (age, socioeconomic status, and race), attributes of place that reduce or amplify exposure (floodplain, coastal zone, and urban heat island), and the resilience of critical public health infrastructure.

Amplification of existing health threats: The effects of extreme heat and heat waves, projected worsening air pollution and asthma, extreme rainfall and flooding, and displacement and injuries associated with extreme weather events, fueled by climate change, are already substantial public health issues. Trends projected under a changing climate are projected to exacerbate these health effects in the future.[62]

Children: The effects of climate change increase vulnerability of children to extreme heat, and increased health damage (morbidity, mortality) resulting from heat waves has been well documented.[16,22,51,53,140] Extreme heat also causes more pediatric deaths,[47,48] and more emergency room visits and hospital admissions.[49,50] Adverse effects from increased heavy precipitation can lead to more pediatric deaths, waterborne diseases,[66] and illness.[141]

The elderly: Heat stress is especially damaging to the health of older people,[45,49,60,133,142,209] as are climate-sensitive increases in air pollution.

The sick: People and communities lacking the resources to adapt or to enhance mobility and escape health-sensitive situations are at relatively high risk.[164]

The poor: People and communities lacking the resources to adapt or to move and escape health-sensitive situations are at relatively high risk.[164]

Some communities of color: There are racial disparities in climate-sensitive exposures to extreme heat in urban areas, and in access to means of adaptation – for example air conditioning use.[149,151,157,211] There are also racial disparities in withstanding, and recovering from, extreme weather events.[155,162]

Climate change will disproportionately impact low-income communities and some communities of color, raising environmental justice concerns.[139,149,151,154,155,157,161,164] Existing health disparities[153,158,159] and other inequities[161] increase vulnerability. For example, Hurricane Katrina demonstrated how vulnerable these populations were to extreme weather events because many low-income and of-color New Orleans residents were killed, injured, or had difficulty evacuating and recovering from the storm.[155,162] Other climate change related issues that have an equity component include heat waves and air quality.[139,149,154,164]

New information and remaining uncertainties

Important new evidence[45] confirmed findings from a prior literature review.[139]

The potential for specific climate-vulnerable communities to experience highly harmful health effects is not entirely clear in specific regions and on specific time frames due to uncertainties in rates of adaptation and uncertainties about the outcome of public health interventions currently being implemented that aim to address underlying health disparities and determinants of health.[206] The public health community has not routinely conducted evaluations of the overall success of adaptation interventions or of particular elements of those interventions.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence that climate change will amplify existing health threats: **Very High**.

Among those especially vulnerable are:

Children: **Very High**.

The elderly: **Very High**.

The sick: **Very High**.

The poor: **Very High**.

Some communities of color: **High**.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast United States. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of studies have demonstrated that prevention activities that reduce carbon pollution, like using alternative energy sources[174] and using active transportation like biking or walking,[188] can lead to significant public health benefits, which can save costs in the near and long term.[176] Health impacts associated with climate change can be prevented through early action at significantly lower cost than dealing with them after they occur. For example, heat wave early warning systems are much less expensive than treating heat-related illnesses.[165] Existing adaptation programs have improved public health resilience.[9,153] One survey highlighted opportunities to address climate change preparedness activities and climate-health research[181] before needs become more widespread.

Considering U.S. public health in general, the cost-effectiveness of many prevention activities is well established.[183] Some preventive actions are cost-saving, while others are deemed cost-effective based on a pre-determined threshold. Early preventive interventions, such as early warnings for extreme weather, can be particularly cost-effective.[166] However, there is less information on the cost-effectiveness of specific prevention interventions relevant to climate sensitive health threats (for example, heat early warning systems). Overall, we have high confidence that public health actions can do much to protect people from some of the impacts of climate change, and that early action provides the largest health benefits.

The inverse relationship between the magnitude of an impact and a community's ability to adapt is well established and understood. Two extreme events, Hurricane Katrina and the European heat wave of 2003, illustrate this relationship well.[167] Extreme events interact with social vulnerability to produce extreme impacts, and the increasing frequency of extreme events associated with climate change is prompting concern for impacts that may overwhelm adaptive capacity.[62,173] This is equally true of the public health sector, specifically, leading to very high confidence that as threats increase, our ability to adapt to future changes may be limited.

New information and remaining uncertainties

A key issue (uncertainty) is the extent to which the nation, states, communities and individuals will be able to adapt to climate change because this depends on the levels of local exposure to climate-health threats, underlying susceptibilities, and the capacities to adapt that are available at each scale. Overall, the capacity of the American public health and health care delivery systems faces many challenges.[182] The cost of dealing with current health problems is diverting resources from preventing them in the first place. This makes the U.S. population more vulnerable.[56,183]

Steps for improving the information base on adaptation include undertaking a more comprehensive evaluation of existing climate-health preparedness programs and their effectiveness in various jurisdictions (cities, counties, states, nationally).

Assessment of confidence based on evidence

Overall, given the evidence base and remaining uncertainties: **High**.

High: Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Prevention provides the most protection; but we do not as yet have a lot of post-implementation information with which to evaluate preparedness plans.

High: Early action provides the largest health benefits. There is evidence that heat-health early warning systems have saved lives and money in U.S. cities like Philadelphia, PA.[165]

Very High: Our ability to adapt to future changes may be limited.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast U.S. regions.[210] Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of studies have explored the opportunities available to improve health and well-being as a result of adapting to climate change,[176] with many recent publications illustrating the benefit of reduced air pollution.[6,174,175,195] Additionally, some studies have looked at the co-benefits to climate change and health of applying innovative urban design practices which reduce energy consumption and pollution while increasing public health,[99,188,197,198] decrease vulnerability of communities to extreme events[152,197] and reduce the disparity between different societal groups.[206,207,212]

New information and remaining uncertainties

More studies are needed to fully evaluate both the intended and unintended health consequences of efforts to improve the resiliency of communities and human infrastructure to climate change impacts. There is a growing recognition that the magnitude of these health co-benefits or co-harms could be significant, both from a public health and an economic standpoint. [176,188,189]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **Very High**.

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Climate Change Impacts in the United States

CHAPTER 10
ENERGY, WATER, AND LAND USE

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On the Web: http://nca2014.globalchange.gov/report/sectors/energy-water-and-land

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

10 ENERGY, WATER, AND LAND USE

Key Messages

1. **Energy, water, and land systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate change vulnerability as well as adaptation and mitigation options for different regions of the country.**
2. **The dependence of energy systems on land and water supplies will influence the development of these systems and options for reducing greenhouse gas emissions, as well as their climate change vulnerability.**
3. **Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is challenging, but can improve the identification and evaluation of options for reducing climate change impacts.**

Energy, water, and land systems interact in many ways. Energy projects (energy production and delivery) require varying amounts of water and land; water projects (water supply and irrigation) require energy and land; and land-based activities (agriculture and forestry) depend upon energy and water. Increasing population and a growing economy intensify these interactions.[1] Each sector is directly impacted by the others and by climate change, and each sector is a target for adaptation and mitigation efforts. Better understanding of the connections between and among energy, water, and land systems can improve our capacity to predict, prepare for, and mitigate climate change.

Challenges from climate change will arise from long-term, gradual changes, such as sea level rise, as well as from projected changes in weather extremes that have more sudden impacts. The independent implications of climate change for the energy, water, and land sectors have been studied extensively (see Ch. 4: Energy, Ch. 3: Water, and Ch. 13: Land Use & Land Cover Change). However, there are few analyses that capture the interactions among and competition for resources within these three sectors.[1] Very little information is available to evaluate the implications for decision-making and planning, including legal, social, political, and other decisions.

Climate change is not the only factor driving changes. Other environmental and socioeconomic stressors interact with climate change and affect vulnerability and response strategies with respect to energy, water, and land systems. The availability and use of energy, water, and land resources and the ways in which they interact vary across the nation. Regions in the United States differ in their 1) energy mix (solar, wind, coal, geothermal, hydropower, nuclear, natural gas, petroleum, ethanol); 2) observed and projected precipitation and temperature patterns; 3) sources and quality of available water resources (for example, ground, surface, recycled); 4) technologies for storing, transporting, treating and using water; and 5) land use and land cover (see Ch. 13: Land Use & Land Cover Change). Decision-making processes for each sector also differ, and decisions often transcend scales, from local to state to federal, meaning that mitigation and adaptation options differ widely.

Energy, Water, Land, and Climate Interactions

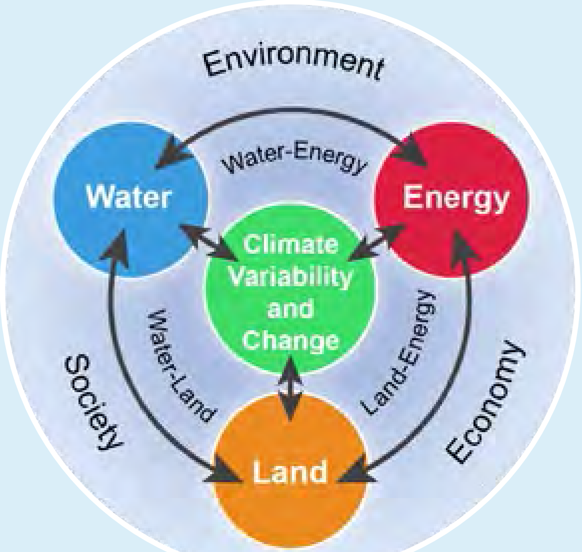


Figure 10.1. The interactions between and among the energy, water, land, and climate systems take place within a social and economic context. (Figure source: Skaggs et al. 2012[1]).

Given the many mitigation and adaptation opportunities available through the energy sector, a focus on energy is a useful way to highlight the interactions among energy, water, and land as well as intersections with climate and other stressors. For example, energy production already competes for water resources with agriculture, direct human uses, and natural systems. Climate-driven changes in land cover and land use are projected to further affect water quality and availability, increasing the competition for water needed for energy production. In turn, diminishing water quality and availability means that there will be a need for more energy to purify water and more infrastructure on land to store and distribute water. Stakeholders need to understand the interconnected nature of climate change impacts, and the value of assessments would be improved if risks and vulnerabilities were evaluated from a cross-sector standpoint.[2]

Key Message 1: Cascading Events

Energy, water, and land systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate change vulnerability as well as adaptation and mitigation options for different regions of the country.

Energy production, land use, and water resources are linked in increasingly complex ways. In some parts of the country, electric utilities and energy companies compete with farmers and ranchers, other industries, and municipalities for water rights and availability, which are also constrained by interstate and international commitments. Private and public sector decision-makers must consider the impacts of strained water supplies on agricultural, ecological, industrial, urban, and public health needs. Across the country, these intertwined sectors will witness increased stresses due to climate changes that are projected to lower water quality and/or quantity in many regions and change heating and cooling electricity demands.

Coast-to-Coast 100-degree Days in 2011

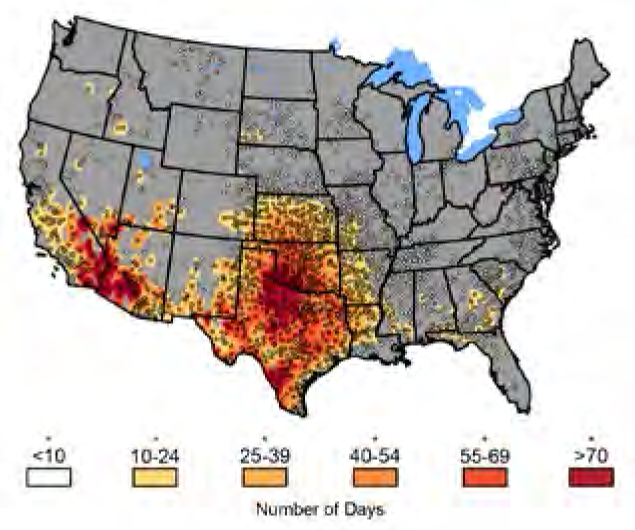


Figure 10.2. Map shows numbers of days with temperatures above 100°F during 2011. The black circles denote the location of observing stations recording 100°F days. The number of days with temperatures exceeding 100°F is expected to increase. The record temperatures and drought during the summer of 2011 represent conditions that will be more likely in the U.S. as climate change continues. When outdoor temperatures increase, electricity demands for cooling increase, water availability decreases, and water temperatures increase. Alternative energy technologies may require little water (for example, solar and wind) and can enhance resilience of the electricity sector, but still face land-use and habitat considerations. The projected increases in drought and heat waves provide an example of the ways climate changes will challenge energy, water, and land systems. (Figure source: NOAA NCDC, 2012).

The links between and among energy, water, and land sectors mean that they are susceptible to cascading effects from one sector to the next. An example is found in the drought and heat waves experienced across much of the U.S. during the summers of 2011 and 2012. In 2011, drought spread across the south-central U.S., causing a series of energy, water, and land impacts that demonstrate the connections among these sectors. Texans, for example, experienced the hottest and driest summer on record. Summer average temperatures were 5.2°F higher than normal, and precipitation was lower than previous records set in 1956. The associated heat wave, with temperatures above 100°F for 40 consecutive days, together with drought, strained the region's energy and water resources.[3,4,5]

These extreme climate events resulted in cascading effects across energy, water, and land systems. High temperatures caused increased demand for electricity for air conditioning, which corresponded to increased water withdrawal and consumption for electricity generation. Heat, increased evaporation, drier soils, and lack of rain led to higher irrigation demands, which added stress on water resources required for energy production. At the same time, low-flowing and warmer rivers threatened to suspend power plant production in several locations, reducing the options for dealing with the concurrent increase in electricity demand.

The impacts on land resources and land use were dramatic. Drought reduced crop yields and affected livestock, costing Texas farmers and ranchers more than $5 billion, a 28% loss compared to average revenues of the previous four years.[6] With increased feed costs, ranchers were forced to sell livestock at lower profit. Drought increased tree mortality,[7] providing more fuel for record wildfires that burned 3.8 million acres (an area about the size of Connecticut) and destroyed 2,763 homes.[8]

Texas Summer 2011:
Record Heat and Drought

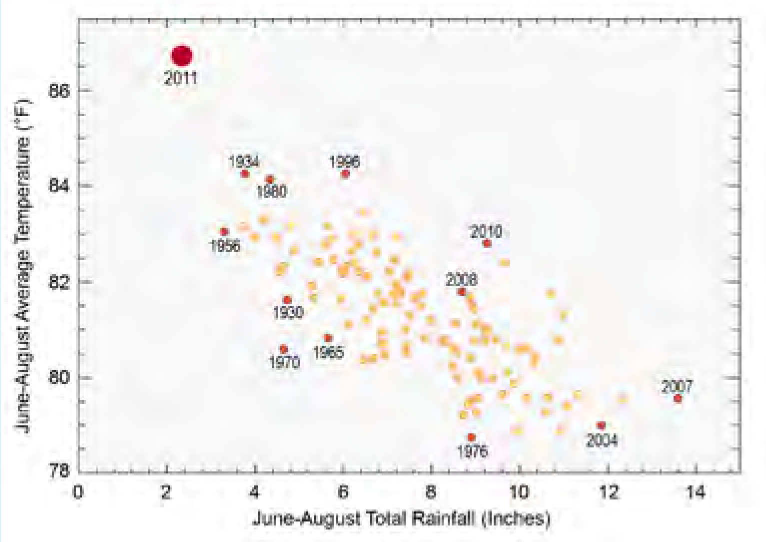


Figure 10.3. Graph shows average summer temperature and total rainfall in Texas from 1919 through 2012. The red dots illustrate the range of temperatures and rainfall observed over time. The record temperatures and drought during the summer of 2011 (large red dot) represent conditions far outside those that have occurred since the instrumental record began.[4] An analysis has shown that the probability of such an event has more than doubled as a result of human-induced climate change[3]. (Figure source: NOAA NCDC / CICS-NC).

Energy, water, and land interactions complicated and amplified the direct impacts on the electric sector. With electricity demands at all-time highs, water shortages threatened more than 3,000 megawatts of generating capacity – enough power to supply more than one million homes.[9] As a result of the record demand and reduced supply, marginal electricity prices repeatedly hit $3,000 a megawatt hour, which is three times the maximum amount that generators can charge in deregulated electricity markets in the eastern United States.[10]

Competition for water also intensified. More than 16% of electricity production relied on cooling water from sources that shrank to historically low levels,[9] and demands for water used to generate electricity competed with simultaneous demands for agriculture and other human activities. City and regional managers rationed water to farms and urban areas, and in some instances, water was trucked to communities that lacked sufficient supplies.[11] As late as January 2012, customers of 1,010 Texas water systems were being asked to restrict water use; mandatory water restrictions were in place in 647 water systems.[12] At the same time, changing vegetation attributes, grazing, cropping, and wildfire compromised water quality and availability, increasing the amount of power required for water pumping and purification.

The Texas example shows how energy, land, water, and weather interacted in one region. Extreme weather events may affect other regions differently, because of the relative vulnerability of energy, water, and land resources, linkages, and infrastructure. For example, sustained droughts in the Northwest will affect how water managers release water from reservoirs, which in turn will affect water deliveries for ecosystem services, irrigation, recreation, and hydropower. Further complicating matters, hydropower is increasingly being used to balance variable wind generation in the Northwest, and seasonal hydroelectric restrictions have already created challenges to fulfilling this role. In the Midwest, drought poses challenges to meeting electricity demands because diminished water availability and elevated water temperatures reduce the efficiency of electricity generation by thermoelectric power plants. To protect water quality, federal and state regulations can require suspension of operations of thermoelectric power plants if water used to cool the power plants exceeds established temperature thresholds as it is returned to streams.

Energy, land, water, and weather interactions are not limited to drought. For instance, 2011 also saw record flooding in the Mississippi basin. Floodwaters surrounded the Fort Calhoun nuclear power plant in Nebraska, shut down substations, and caused a wide range of energy, land, and water impacts (Ch. 3: Water).

Interactions of Energy, Water, and Land Uses

Figure 10.4 depicts the current mix of energy, water, and land use within each U.S. region. The mixes reflect competition for water and land resources, but more importantly for the purposes here, the mixes reflect linkages across the energy, water, and land sectors as well as linkages to climate. For example, higher water withdrawal for thermoelectric power (power plants that use a steam cycle to generate electricity) generally reflects electric generation technology choices (often coal-, gas-, or nuclear-fired generation with open loop cooling) that assume the availability of large quantities of water. Therefore, the choice of energy technology varies based on the available resources in a region. Similarly, land-water linkages are evident in cropland and agricultural water use. The potential growth in renewable energy may strengthen the linkage between energy and land (see "Examples of Energy, Water, and Land Linkages"). Climate change affects each sector directly and indirectly. For instance, climate change affects water supplies, energy demand, and land productivity, all of which can affect sector-wide decisions.

Regional Water, Energy, and Land Use, with Projected Climate Change Impacts

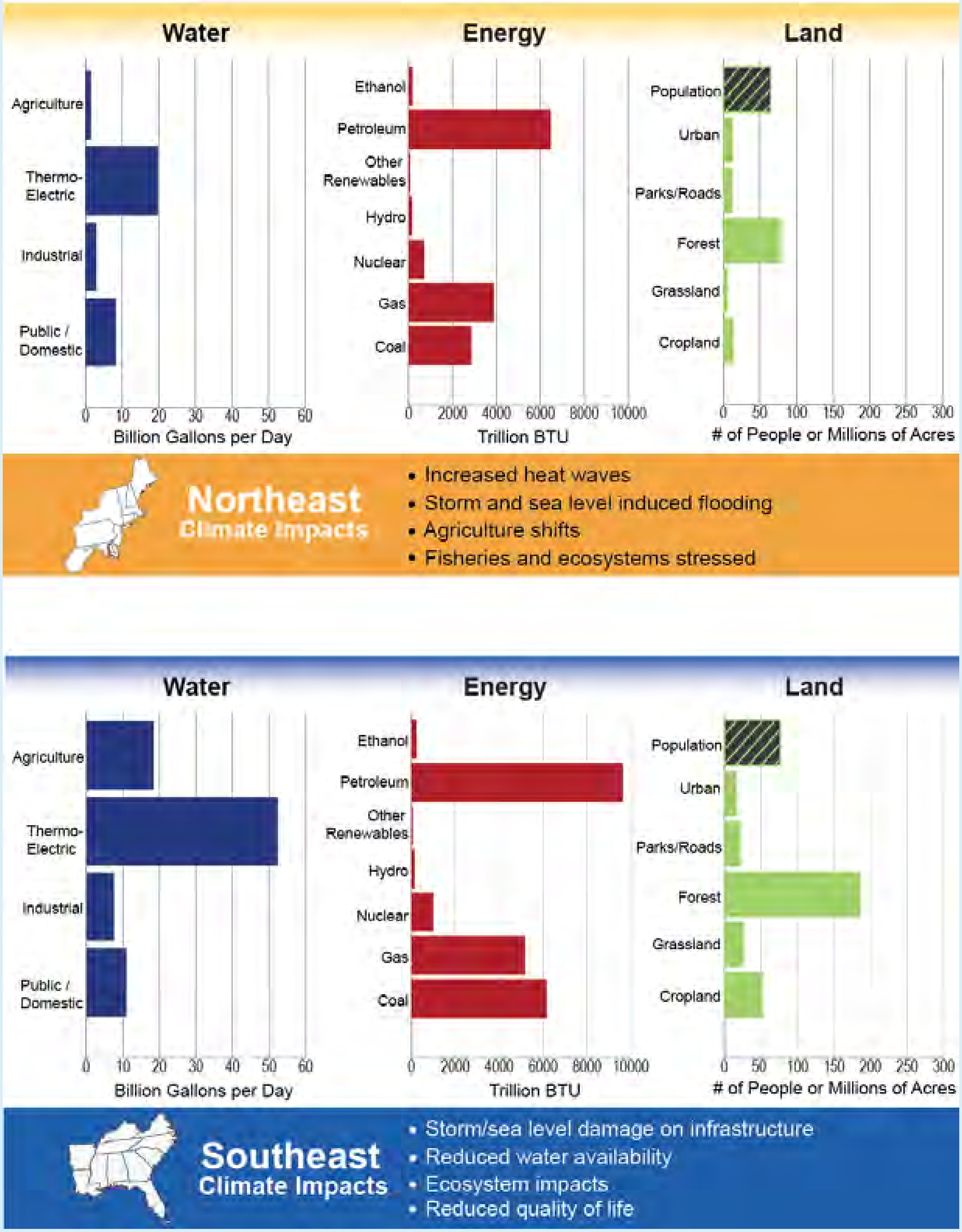
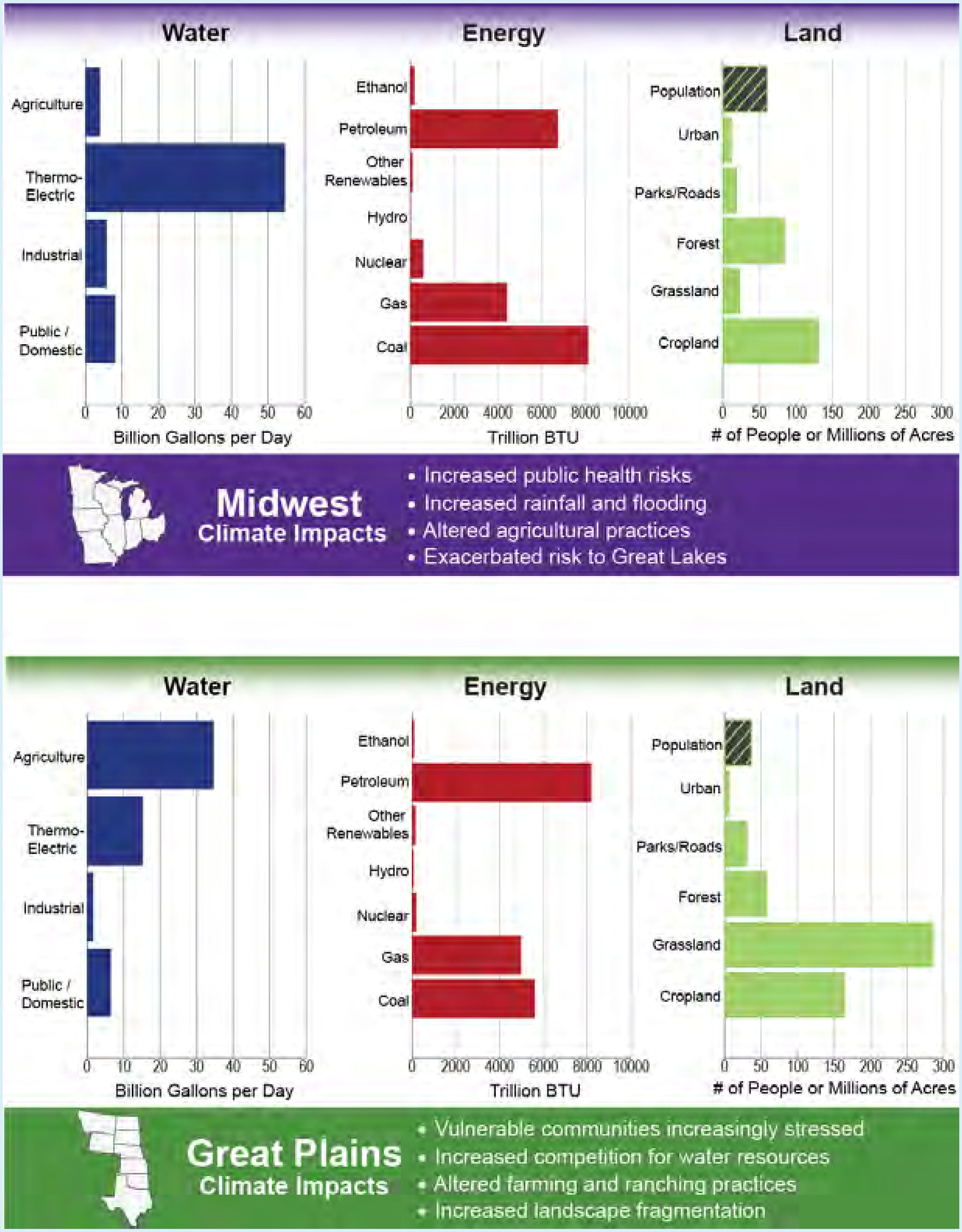


Figure 10.4. U.S. regions differ in the manner and intensity with which they use, or have available, energy, water, and land. Water bars represent total water withdrawals in billions of gallons per day (except Alaska and Hawaiʻi, which are in millions of gallons per day); energy bars represent energy production for the region in 2012; and land represents land cover by type (green bars) or number of people (black and green bars). Only water withdrawals, not consumption, are shown (see Ch. 3: Water). Agricultural water withdrawals include irrigation, livestock, and aquaculture uses. (Data from EIA 2012[13] [energy], Kenny et al. 2009[14] [water], and USDA ERS 2007[15] [land]).

Regional Water, Energy, and Land Use, with Projected Climate Change Impacts



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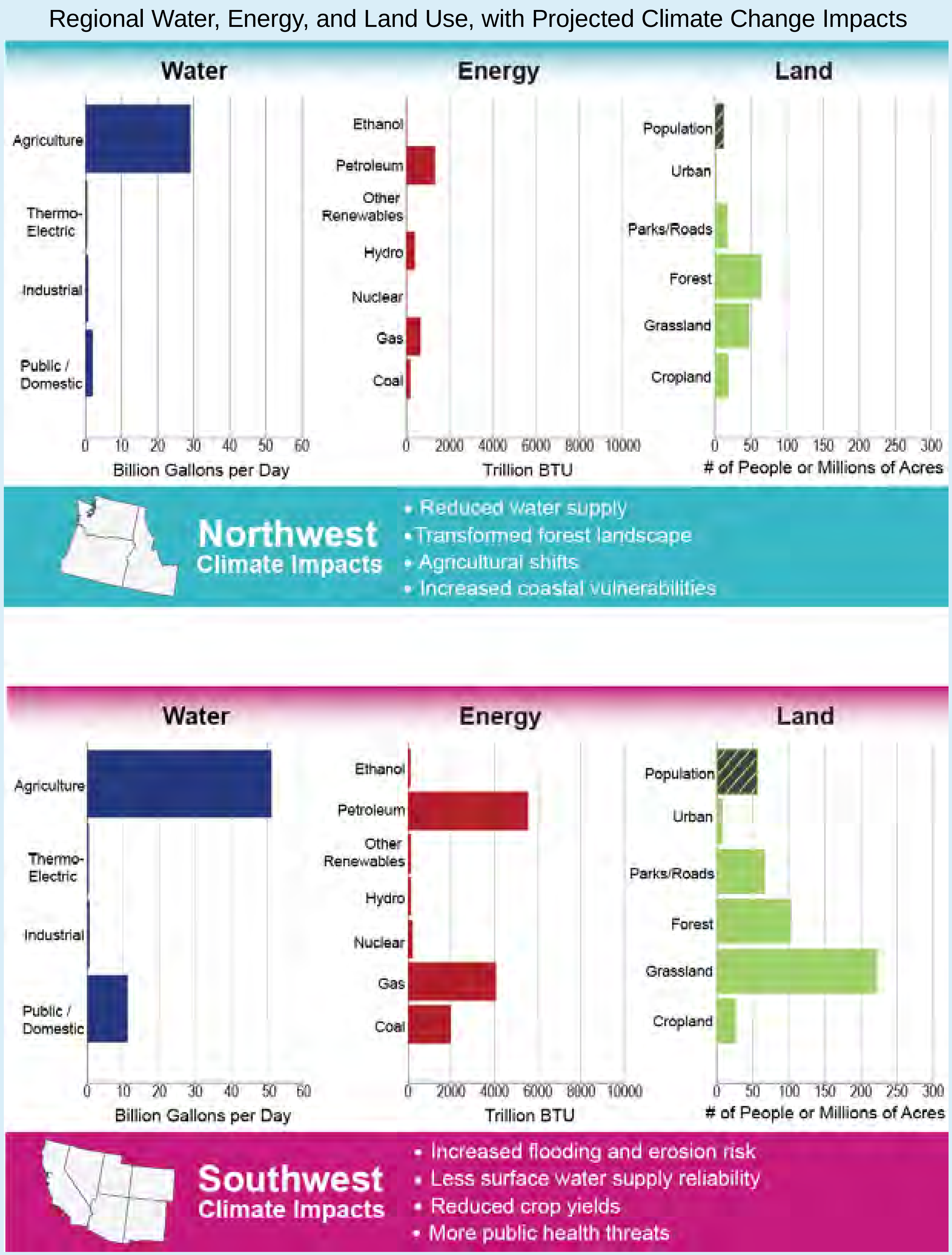

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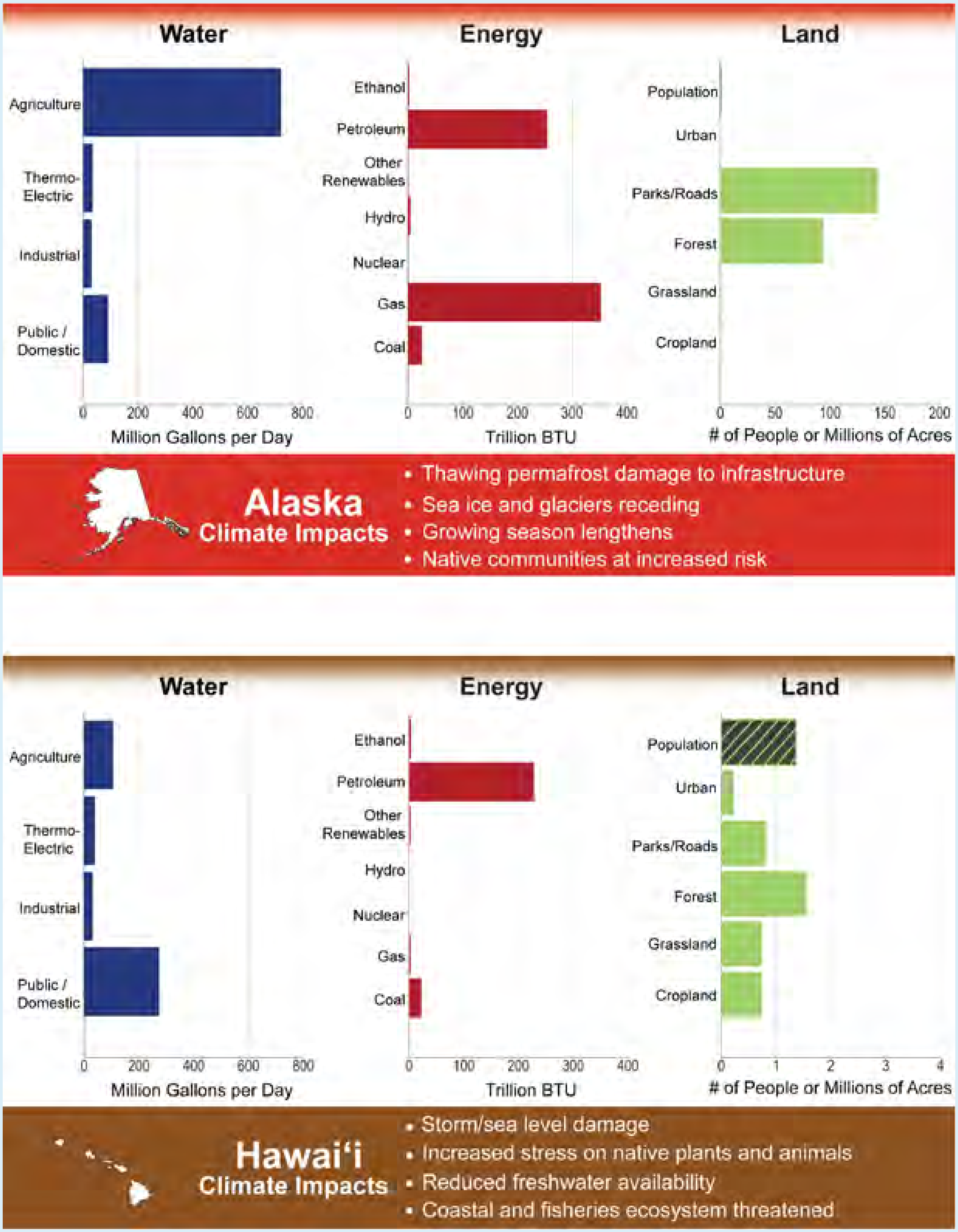
Regional Water, Energy, and Land Use, with Projected Climate Change Impacts



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Key Message 2: Options for Reducing Emissions and Climate Vulnerability

The dependence of energy systems on land and water supplies will influence the development of these systems and options for reducing greenhouse gas emissions, as well as their climate change vulnerability.

Interactions among energy, water, and land resources have influenced and will continue to influence selection and operation of energy technologies. In some situations, land and water constraints also pose challenges to technology options for reducing

Water Use for Electricity Generation by Fuel and Cooling Technology

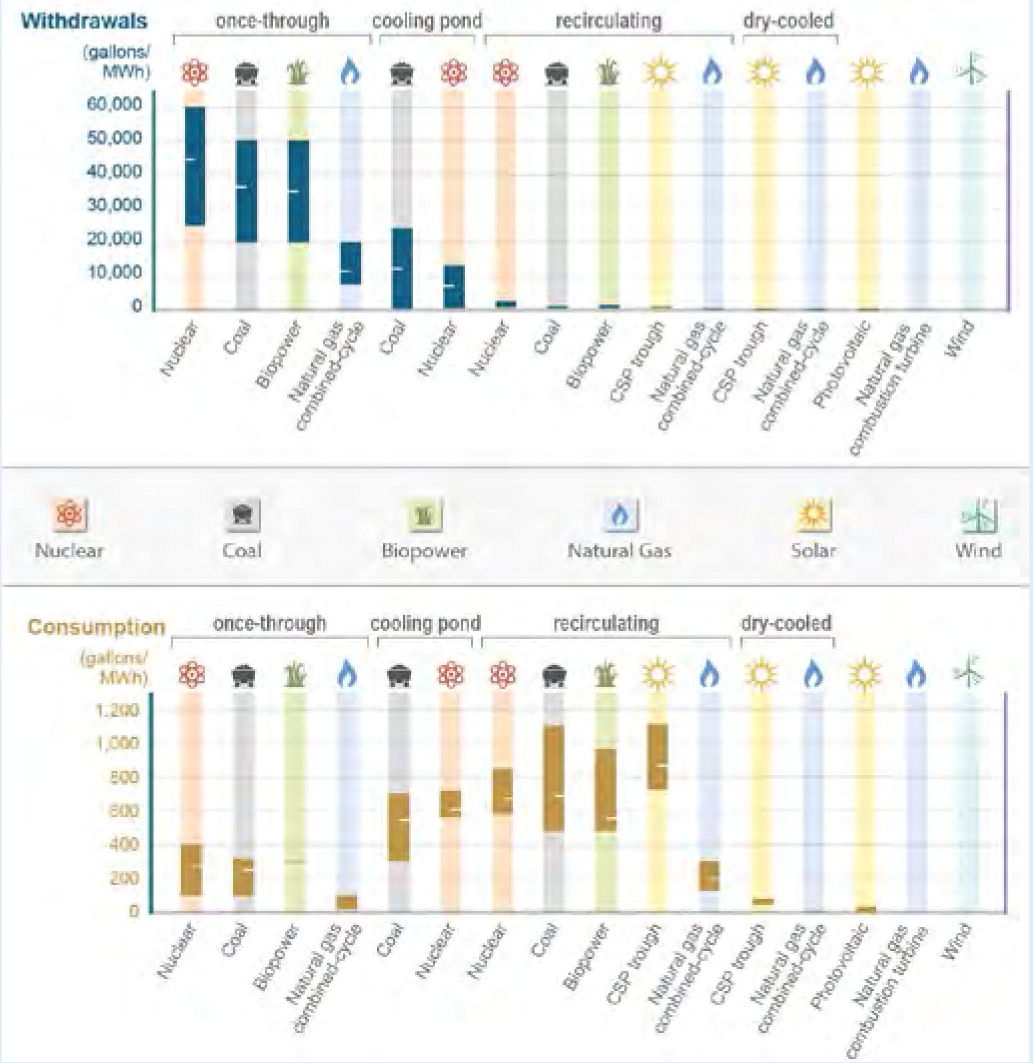

Figure 10.5. Technology choices can significantly affect water and land use. These two panels show a selection of technologies. Ranges in water withdrawal/consumption reflect minimum and maximum amounts of water used for selected technologies. Carbon dioxide capture and storage (CCS) is not included in the figures, but is discussed in the text. The top panel shows water withdrawals for various electricity production methods. Some methods, like most conventional nuclear power plants that use "once-through" cooling systems, require large water withdrawals but return most of that water to the source (usually rivers and streams). For nuclear plants, utilizing cooling ponds can dramatically reduce water withdrawal from streams and rivers, but increases the total amount of water consumed. Beyond large withdrawals, once-through cooling systems also affect the environment by trapping aquatic life in intake structures and by increasing the temperature of streams.[18] Alternatively, once-through systems tend to operate at slightly better efficiencies than plants using other cooling systems. The bottom panel shows water consumption for various electricity production methods. Coal-powered plants using recirculating water systems have relatively low requirements for water withdrawals, but consume much more of that water, as it is turned into steam. Water consumption is much smaller for various dry-cooled electricity generation technologies, including for coal, which is not shown. Although small in relation to cooling water needs, water consumption also occurs throughout the fuel and power cycle.[19] (Figure source: Averyt et al. 2011[20]).

greenhouse gas emissions. For example, with the Southwest having most of the potential for deployment of concentrating solar technologies, facilities will need to be extremely water-efficient in order to compete for limited water resources. While wind farms avoid impacts on water resources, issues concerning land use, wildlife impacts, the environment, and aesthetics are often encountered. Raising crops to produce biofuels uses arable land and water that might otherwise be available for food production. This fact came into stark focus during the summer of 2012, when drought caused poor corn harvests, intensifying concerns about allocation of the harvest for food versus ethanol.[16]

Competition for water supplies is encouraging deployment of technologies that are less water-intensive than coal or nuclear power with once-through cooling. For example, wind, natural gas, photovoltaic (solar electric), and even thermoelectric generation with dry cooling use less water. Challenges in siting land- and water-intensive energy facilities are likely to intensify over time as competition for these resources grows. Considering the interactions among energy, water, and land systems presents opportunities for further identification and implementation of energy options that can reduce emissions, promote resilience, and improve sustainability.

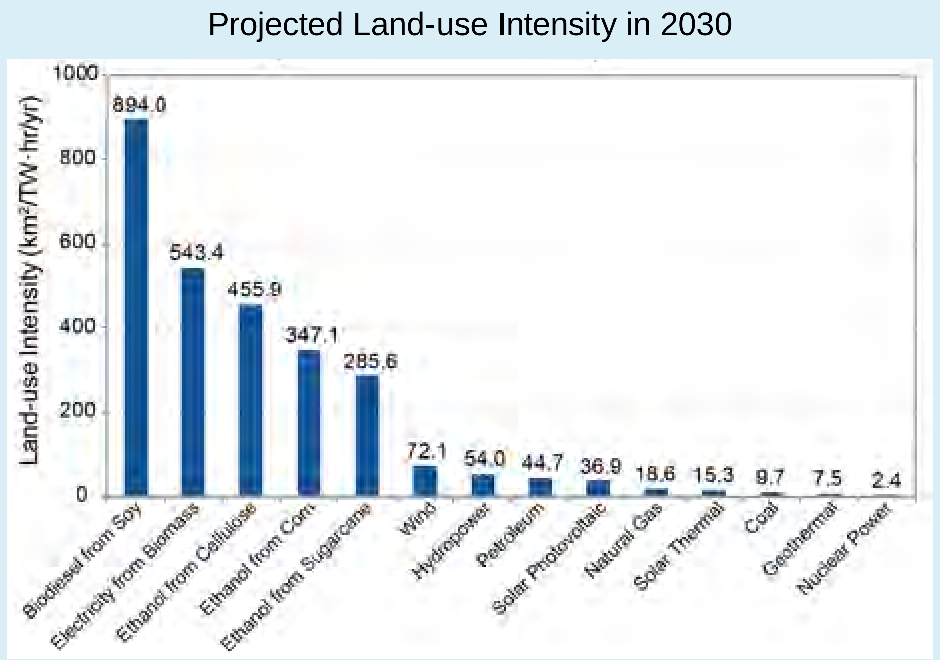

Figure 10.6. The figure shows illustrative projections for 2030 of the total land-use intensity associated with various electricity production methods. Estimates consider both the footprint of the power plant as well as land affected by energy extraction. There is a relatively large range in impacts across technologies. For example, a change from nuclear to wind power could mean a significant change in associated land use. For each electricity production method, the figure shows the average of a most-compact and least-compact estimate for how much land will be needed per unit of energy. The figure uses projections from the Energy Information Administration Reference scenario for the year 2030, based on energy consumption by fuel type and power plant "capacity factors" (the ratio of total power generation to maximum possible power generation). The most-compact and least-compact estimates of biofuel land-use intensities reflect differences between current yield and production efficiency levels and those that are projected for 2030 assuming technology improvements.[21] (Figure source: adapted from McDonald et al. 2009[21]).

Every option for reducing greenhouse gas emissions involves tradeoffs that affect natural resources, socioeconomic systems, and the built environment. Energy system technologies vary widely in their carbon emissions and their use of water and land. As such, there are energy-water-land tradeoffs and synergies with respect to adaptation and mitigation. Each choice involves assessing the relative importance of the tradeoffs related to these resources in the context of both short- and long-term risks (see "Examples of Energy, Water, and Land Linkages" that describes four technologies that could play key roles). Figure 10.5 provides a systematic comparison of water withdrawals and consumptive use, illustrating the wide variation across both electric generation technologies and the accompanying cooling technologies. Carbon dioxide capture and storage (CCS) is not included in the chart, but coal-fired


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Table 10.1. Energy, water, and land sectoral impacts associated with a sample of climate mitigation and adaptation measures. Plus sign means a positive effect (reduced stress) on sector, minus sign means a negative effect (increased stress) on sector. Blank means effect not noted. Blue means consideration of energy extraction and power plant processes. It is important to keep in mind that this table only reflects physical synergies and tradeoffs. There are, of course, economic tradeoffs as well in the form of technology costs and societal concerns, such as energy security, food security, and water quality. Expansion of hybrid or dry-cooled solar technologies, versus wet, could help reduce water risks. For a more detailed description of the entries in the table, see Skaggs et al. 2012.[1] Additional considerations regarding energy extraction, power plant processes, and energy use associated with irrigation were added to those reflected in Skaggs et al. 2012[1] (Adapted from Skaggs et al. 2012[1]).

Mitigation measures	Water	Land	Energy
Switch from coal to natural gas fueled power plants	+ and –	+ and –	
Expand CCS to fossil-fueled power plant	–	–	
Expansion of nuclear power	–		
Expansion of wind	+	–	
Expansion of solar thermal technologies (wet cooled)	–	–	
Expansion of commercial scale photovoltaic	+	–	
Expansion of hydropower	+ and –	–	+
Expansion of biomass production for energy	+ and –	+ and –	
Adaptation measures	**Water**	**Land**	**Energy**
Switch from once-through to recirculating cooling in thermoelectric power plants	+ and –		-
Switch from wet to dry cooling at thermoelectric power plants	+		-
Desalinization	+ and –	+	+ and –
New storage and conveyance of water	+ and –	–	–
Switch to drought-tolerant crops in drought vulnerable regions	+	–	+
Increase transmission capacity to urban areas to reduce power outages during high demand periods		–	+

power plants (both evaporative cooling and dry cooling) fitted with CCS would consume twice as much water per unit of electricity generated as similar coal-fired facilities without CCS.[17] Figure 10.6 shows projected land-use intensity in 2030 for various electricity production methods. Describing land use with a single number is valuable, but must be considered with care. For example, while wind generation can require significant amounts of land, it can co-exist with other activities such as farming and grazing, while other technologies may not be compatible with other land uses. Land and water influences on energy production capacity are expected to get stronger in the future, and greater resource scarcity will shape investment decisions.

Every adaptation and mitigation option involves tradeoffs in how it increases or decreases stress on energy systems and water and land resources. For a selected set of mitigation and adaptation measures, Table 10.1 provides a summary illustrating qualitatively how different technologies relate to energy, water, and land.[1]

Particularly relevant to climate change mitigation are the energy, water, and land risks associated with low-carbon electricity generation. For example, expansion of nuclear power and coal power with CCS are two measures that have been discussed as a potential part of a future decarbonized energy system.[22,23] Both are also potentially water intensive and therefore have vulnerabilities related to climate impacts and competing water uses. Alternatively, renewable generation and combined cycle gas and coal have relatively modest water withdrawals (see also EPRI 2011[24]). Overall, energy, water, and land sector vulnerabilities are important factors to weigh in considering alternative electricity generation options and cooling systems.

Bioenergy also presents opportunities for mitigation, but some potential bioenergy feedstocks are land and water intensive. Where land and water resources are limited, bioenergy may therefore be at risk of competing with other uses of land and water, and climate changes present additional challenges. Other mitigation options, such as afforestation (re-establishment of forests), forest management, agricultural soil management, and fertilizer management are also tied intimately into the interfaces among land availability, land management, and water resource quantity and quality.[25]

Some sector-specific mitigation and adaptation measures can provide opportunities to enhance climate mitigation or adaptation objectives in the other sectors. However, other measures may have negative impacts on mitigation or adaptation potential in other sectors. If such cross-sector impacts are not considered, they can diminish the effectiveness of climate mitigation and adaptation actions.


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For example, switching from coal- to natural-gas-fired electricity generation reduces the emissions associated with power generation. Depending on the situation, the switch to natural gas in the energy sector can either improve or reduce adaptive capacity in the water sector. Natural gas can reduce water use for thermoelectric cooling (gas-fired plants require less cooling water), but natural gas extraction techniques consume water, so water availability must be considered. In addition, gas production has the potential to affect land-based ecosystems by, for example, fragmenting habitat and inhibiting wildlife migration. Future improvements in natural gas technologies and water reuse may reduce the possibility of negative impacts on water supplies and enhance the synergies across the energy, water, and land interface. Incorporating consideration of such cross-sector interactions in planning and policy could affect sectoral decisions and decisions related to climate mitigation and adaptation.

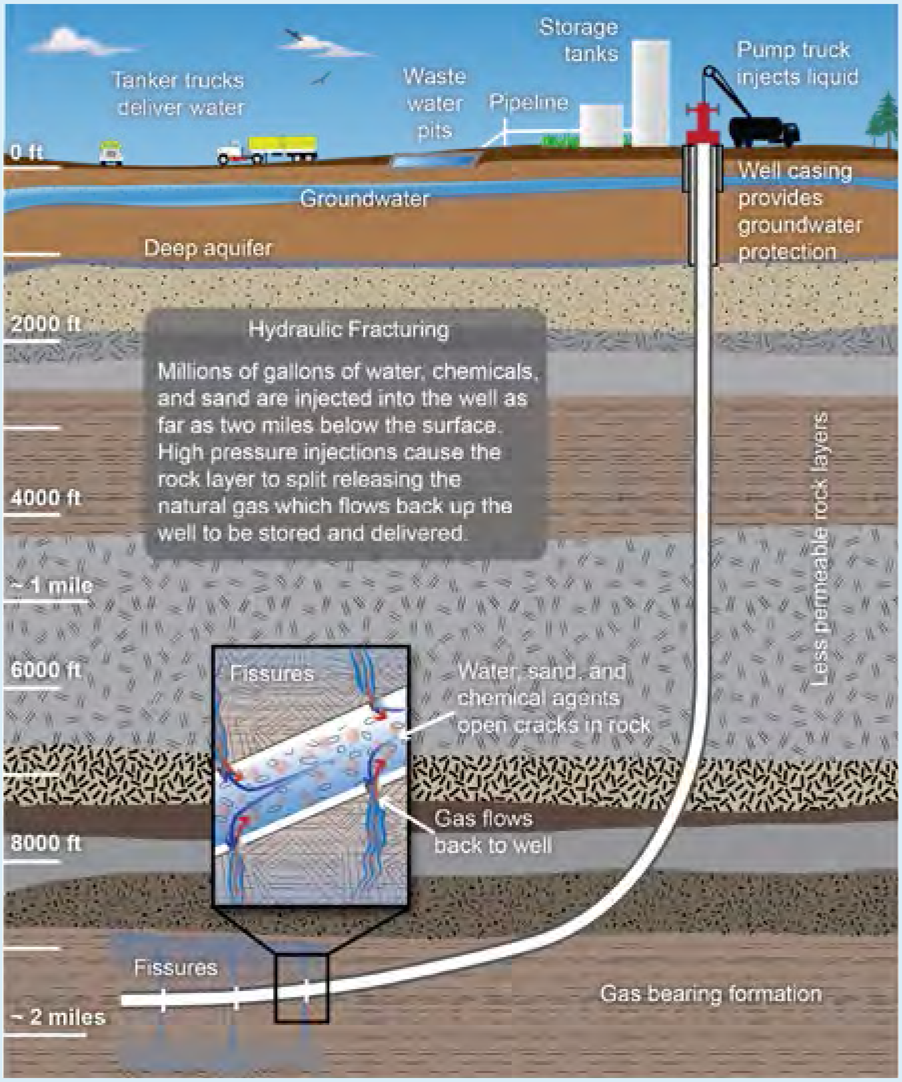
Changes in the availability of water and land due to climate change and other effects of human activities will affect location, design, choice, and operations of energy technologies in the future and, in some cases, constrain their deployment. Energy, water, and land linkages represent constraints, risks, and opportunities for private/public planning and investment decisions. “Examples of Energy, Water, and Land Linkages” below discusses four energy sector technologies that could contribute to reducing U.S. emissions of greenhouse gases and increasing energy security – natural gas from shale, solar power, biofuels, and CCS. These technologies were chosen to illustrate energy, water, and land linkages and other complexities for the design, planning, and deployment of our energy future.

Examples of Energy, Water, and Land Linkages

Shale Natural Gas and Hydraulic Fracturing

The U.S. Energy Information Administration projects a 29% increase in U.S. natural gas production by 2035, driven primarily by the economics of shale gas.[13] As an energy source, natural gas (methane) can have a major advantage over coal and oil: when combusted, it emits less carbon dioxide per unit energy than other fossil fuels, and fewer pollutants like black carbon (soot) and mercury (see Ch. 27: Mitigation). An increase in natural gas consumption could lead to a reduction in U.S. greenhouse gas emissions compared to continued use of other fossil fuels. Disadvantages include the possibility that low-cost gas could supplant deployment of low-carbon generation technologies, such as nuclear power and renewable energy. In addition, the U.S. Environmental Protection Agency estimates that 6.9 million megatons of methane – with a global warming potential equivalent to 144.7 million megatons of CO_2 – is emitted from the U.S. natural gas system through uncontrolled venting and leaks from drilling operations, pipelines, and storage tanks (see Ch. 15: Biogeochemical Cycles; Ch. 27: Mitigation).[26] There is considerable uncertainty about these estimates, and it is an active area of research. While technological improvements may reduce this leakage rate,[26] leakage makes the comparison between natural gas and coal more complex from a climate perspective.[27] For example, methane is a stronger greenhouse gas than carbon dioxide but has a much shorter atmospheric lifetime (see Ch. 15: Biogeochemical Cycles; Ch. 27: Mitigation; Appendix 3: Climate Science; Appendix 4: FAQs).

Hydraulic Fracturing and Water Use



Millions of gallons of water, chemicals, and sand are injected into the well as far as two miles below the surface. High pressure injections cause the rock layer to split releasing the natural gas which flows back up the well to be stored and delivered.

Figure 10.7. Hydraulic fracturing, a drilling method used to retrieve deep reservoirs of natural gas, uses large quantities of water, sand, and chemicals that are injected at high pressure into horizontally-drilled wells as deep as 10,000 feet below Earth's surface. The pressurized mixture causes the rock layer to crack. Sand particles hold the fissures open so that natural gas from the shale can flow into the well. Questions about the water quantity necessary for this extraction method as well as the potential to affect water quality have produced national debate. (Figure source: NOAA NCDC).

Recent reductions in natural gas prices are largely due to advances in hydraulic fracturing, which is a drilling method used to retrieve deep reservoirs of natural gas. Hydraulic fracturing injects large quantities of water, sand, and chemicals at high pressure into horizontally-drilled wells as deep as 10,000 feet below the surface in order to break the shale and extract natural gas.[28] Questions about the water quantity necessary and the potential to affect water quality have produced national

Continued

EXAMPLES OF ENERGY, WATER, AND LAND LINKAGES (CONTINUED)

debate about this method. Federal government and state-led efforts are underway to identify, characterize, and if necessary, find approaches to address these issues (for example, EPA 2011; FracFocus 2012[29]).

A typical shale gas well requires from two to four million gallons of water to drill and fracture (equivalent to the annual water use of 20 to 40 people in the U.S, or three to six Olympic-size swimming pools).[28] The gas extraction industry has begun reusing water in order to lower this demand. However, with current technology, recycling water can require energy-intensive treatment, and becomes more difficult as salts and other contaminants build up in the water with each reuse.[30] In regions where climate change leads to drier conditions, hydraulic fracturing could be vulnerable to climate change related reductions in water supply.

Shale gas development also requires land. To support the drilling and hydraulic fracturing process, a pad, which may be greater than five acres in size, is constructed.[31] Land for new roads, compressor stations, pipelines, and water storage ponds are also required.

The competition for water is expected to increase in the future. State and local water managers will need to assess how gas extraction competes with other priorities for water use, including electricity generation, irrigation, municipal supply, industry use, and livestock production. Collectively, such interactions between the energy and water resource sectors increase vulnerability to climate change, particularly in water-limited regions that are projected to, or become, significantly drier.

Renewable Energy and Land Use

Figure 10.8. Photovoltaic panels convert sunlight directly into electricity. Utility-sized solar power plants require large tracts of land. Photo shows Duke Energy's 113-acre Blue Wing Solar Project in San Antonio, Texas, one of the largest photovoltaic solar farms in the country. (Photo credit: Duke Energy 2010[36]).

Solar Power Generation

Solar energy technologies have the potential to satisfy a significant portion of U.S. electricity demand and reduce greenhouse gas emissions. The land and water requirements for solar power generation depend on the mix of solar technologies deployed. Small-scale (such as rooftop) installations are integrated into current land use and have minimal water requirements. In contrast, utility-scale solar technologies have significant land requirements and can – depending upon the specific generation and cooling technologies – also require significant water resources. For instance, utility-scale photovoltaic systems can require three to ten acres per megawatt (MW) of generating capacity[32] and consume as much as five gallons of water per megawatt hour (MWh) of electricity production. Utility-scale concentrating solar systems can require up to 15 acres per MW[33] and consume 1,040 gallons of water per MWh[34] using wet cooling (and 97% less water with dry cooling). A recent U.S. Department of Energy study concluded that 14% of the U.S. demand for electricity could be met with solar power by 2030.[34] To generate that amount of solar power would require rooftop installations plus about 0.9 million to 2.7 million acres, equivalent to about 1% to 4% of the land area of Arizona, for utility-scale solar power systems and concentrating solar power (CSP).[34]

Recognizing water limitations, most large-scale solar power systems now in planning or development are designed with dry cooling that relies on molten salt or other materials for heat transfer. However, while dry cooling systems reduce the need for water, they have lower plant thermal efficiencies, and therefore reduced production on hot days.[35] Overall, as with other generation technologies, plant designs will have to carefully balance cost, operating issues, and water availability.

Biofuels

Biomass-based energy is currently the largest renewable energy source in the U.S., and biofuels from crops, grass, and trees are the fastest growing renewable domestic bioenergy sector.[13] In 2011, approximately 40 million acres of cropland in the U.S. were used for ethanol production, roughly 16% of the land planted for the eight major field crops.[37] The long-term environmental and social effects of biofuel production and use depend on many factors: the type of feedstock, manage-

Continued

EXAMPLES OF ENERGY, WATER, AND LAND LINKAGES (CONTINUED)

ment practices used to produce them, fuel production and conversion technologies, prior land use, and land- and water-use changes caused by their production and use.[38,39] Biofuels potentially can reduce greenhouse gas emissions by displacing fossil fuel consumption. Biofuels that comply with the Energy Independence and Security Act of 2007 are required to reduce greenhouse gas emissions relative to fossil fuels. In addition, biofuels also have the potential to provide net environmental benefits compared to fossil fuels. For example, ethanol is used as a gasoline additive to meet air quality standards, replacing a previous additive that leaked from storage tanks and contaminated groundwater.[40] However, increases in corn production for biofuel has been cited as contributing to harmful algal blooms.[38]

Currently, most U.S. biofuels, primarily ethanol (from corn) and biodiesel (mainly from soy), are produced from edible parts of crops grown on rain-fed land. Consumptive water use over the life cycle of corn-grain ethanol varies widely, from 15 gallons of water per gallon of gasoline equivalent for rain-fed corn-based ethanol in Ohio, to 1,500 gallons of water per gallon of gasoline equivalent for irrigated corn-based ethanol in New Mexico. In comparison, producing and refining petroleum-based fuels uses 1.9 to 6.6 gallons of water per gallon of gasoline.[38,41]

The U.S. Renewable Fuels Standard (RFS) aims to expand production of cellulosic ethanol to at least 16 billion gallons per year by 2022. Cellulosic biofuels, derived from the entire plant rather than just the food portions, potentially have several advantages, such as fewer water quality impacts,[42] less water consumption, and the use of forest-derived feedstocks.[38] Cellulosic biofuels have not yet been produced in large volumes in the United States. The RFS target could require up to an additional 30 to 60 million acres of land, or alternatively be sourced from other feedstocks, such as forest and agricultural residues and municipal solid waste, but such supplies are projected to be inadequate for meeting the full cellulosic biofuel standard.[38]

Conversion of land not in cropland to crops for biofuel production may increase water consumption and runoff of fertilizers, herbicides, and sediment.[43] The impacts of climate change, particularly in areas where water availability may decrease (see Ch. 2: Our Changing Climate, Ch. 3: Water, and Ch. 6: Agriculture), however, may make it increasingly difficult to raise crops in arid regions of the country. The use of crops that are better suited to arid conditions and are efficient in recycling nutrients, such as switchgrass for cellulosic ethanol, could lower the vulnerability of biofuel production to climate change.[44] Another potential source of biomass for biofuel production is microalgae, but the existing technologies are still not carbon neutral, nor commercially viable.[45]

Carbon Capture and Storage

Carbon capture and storage (CCS) technologies have the potential to capture 90% of CO_2 emissions from coal and natural gas combustion by industrial and electric sector facilities and thus allow continued use of low-cost fossil fuels in a carbon-constrained future.[46] CCS captures CO_2 post- or pre-fuel combustion and injects the CO_2 into geologic formations for long-term storage. In addition, combining CCS with bioenergy applications represents one of a few potential options for actually removing CO_2 from the atmosphere[47] because carbon that was recently in the atmosphere and accumulated by growing plants can be captured and stored.

CCS substantially increases the cost of building and operating a power plant, both through up-front costs and additional energy use during operation (referred to as "parasitic loads" or an energy penalty).[46] Substantial amounts of water are also used to separate CO_2 from emissions and to generate the required parasitic energy. With current technologies, CCS can increase water consumption 30% to 100%.[48] Gasification technologies, where coal or biomass are converted to gases and CO_2 is separated before combustion, reduce the energy penalty and water requirements, but currently at higher capital costs.[49] As with other technologies, technology and design choices for CCS need to be balanced with water requirements and water availability. Climate change will influence the former via effects on energy demand and the latter via precipitation changes. CCS facilities themselves have relatively modest land demands compared to some other generation options. However, bioenergy use with CCS would imply a much stronger land linkage.

CCS facilities for electric power plants are currently operating at pilot scale, and a commercial scale demonstration project is under construction.[50] Although the potential opportunities are large, many uncertainties remain, including cost, demonstration at scale, environmental impacts, and what constitutes a safe, long-term geologic repository for sequestering carbon dioxide.[51]

Key Message 3: Challenges to Reducing Vulnerabilities

Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is challenging, but can improve the identification and evaluation of options for reducing climate change impacts.

The complex nature of interactions among energy, water, and land systems, particularly in the context of climate change, does not lend itself to simple solutions. The energy, water, and land interactions themselves create vulnerabilities to competing resource demands. Climate change is an additional stressor. However, resource management decisions are often focused on just one of these sectors. Where the three sectors are tightly coupled, options for mitigating or adapting to climate change and consideration of the tradeoffs associated with technological or resource availability may be limited. The complex nature of water and energy systems are also highlighted in Chapter 3 (Water), which discusses water constraints in many areas of the U.S., and in Chapter 4 (Energy), where it is noted that there will be challenges across the nation for water quality to comply with thermal regulatory needs for energy production.

A changing climate, particularly in areas projected to be warmer and drier, is expected to lead to drought and stresses on water supply, affecting energy, water, and land sectors in the United States. As the Texas drought of 2011 and 2012 illustrates, impacts to a particular sector, such as energy production, generate consequences for the others, such as water resource availability. Similarly, new energy development and production will require careful consideration of land and water sector resources. As a result, vulnerability to climate change depends on energy, water, and land linkages and on climate risks across all sectors, and decision-making is complex.

Water Stress in the U.S.

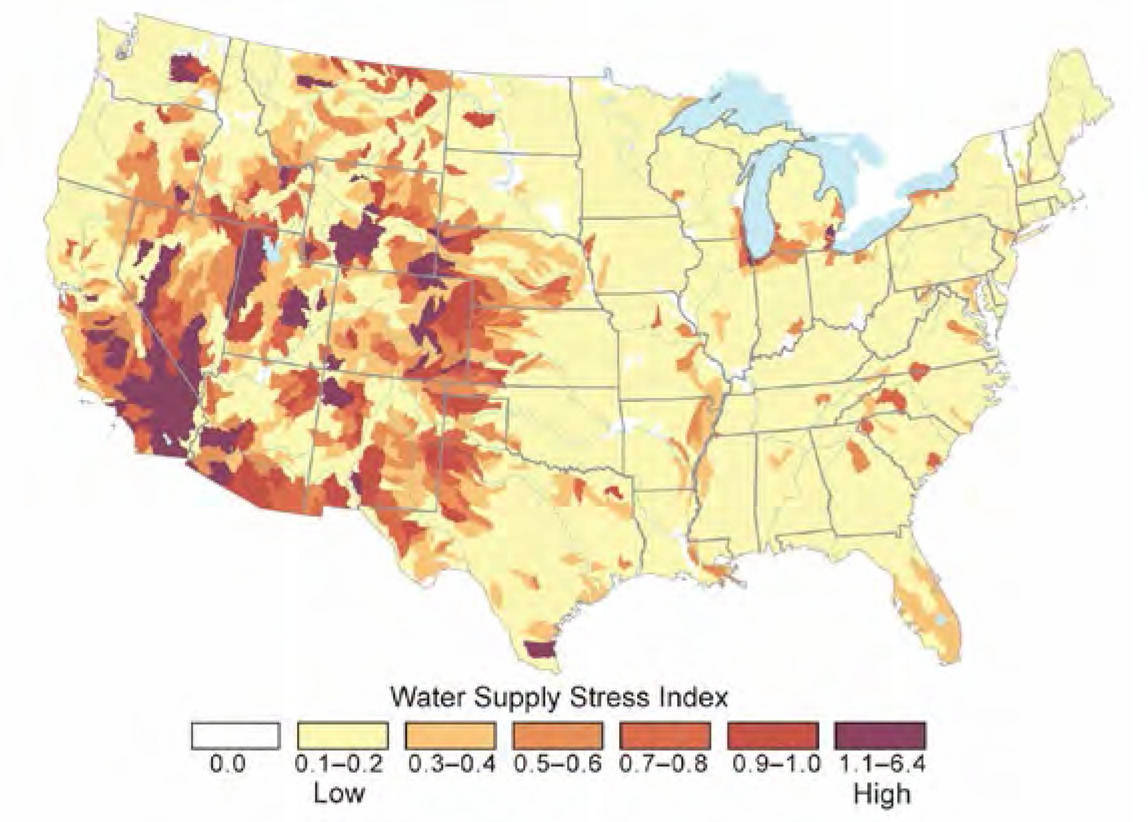


Figure 10.9. In many parts of the country, competing demands for water create stress in local and regional watersheds. Map shows a "water supply stress index" for the U.S. based on observations, with widespread stress in much of the Southwest, western Great Plains, and parts of the Northwest. Watersheds are considered stressed when water demand (from power plants, agriculture, and municipalities) exceeds 40% (water supply stress index of 0.4) of available supply. (Figure source: Averyt et al. 2011[20]).

The Columbia River Basin Land Use and Land Cover

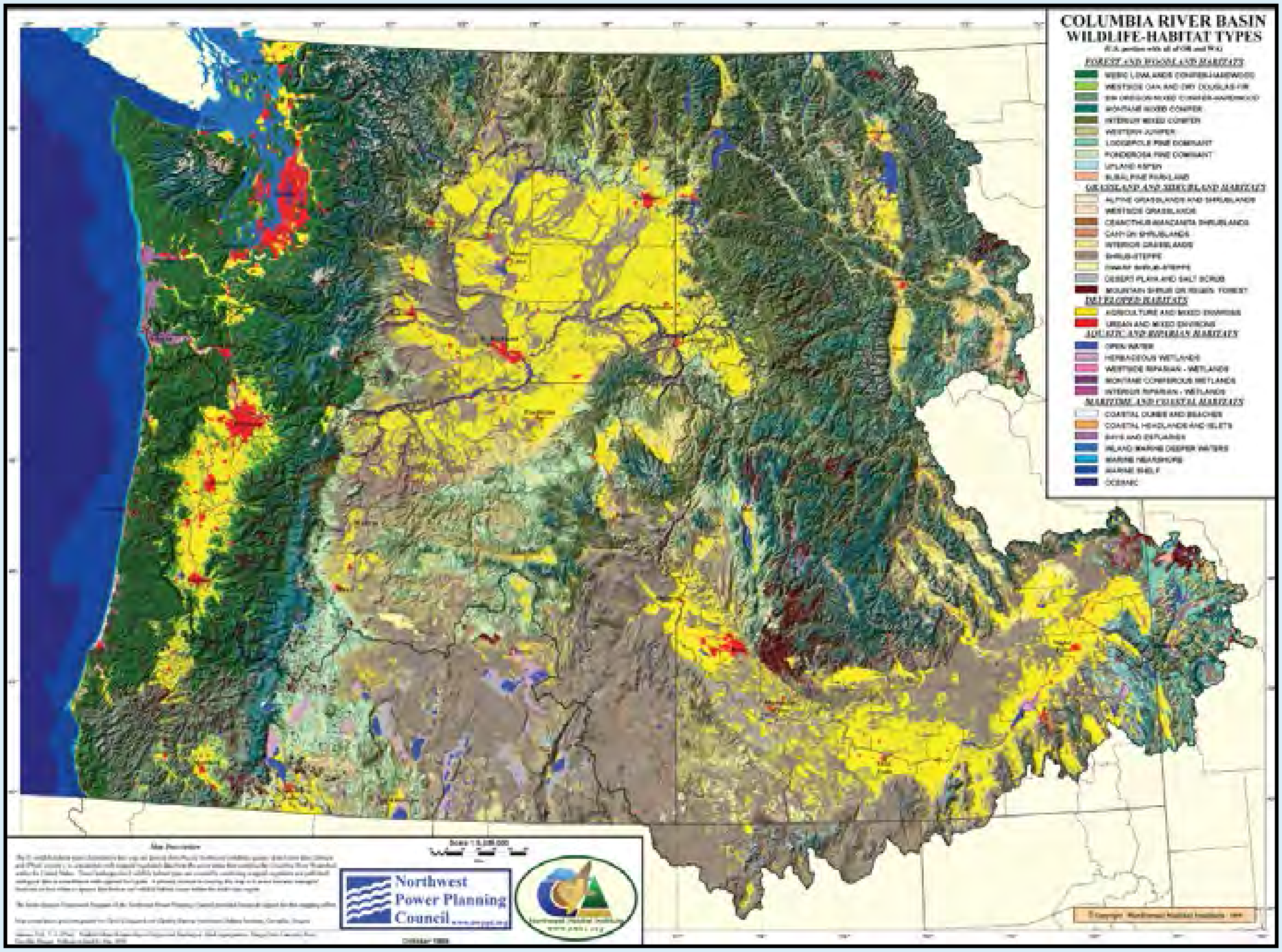


Figure 10.10. Agriculture is in yellow, forests are shades of green, shrublands are gray, and urban areas are in red. The river is used for hydropower generation, flood control, agriculture irrigation, recreation, support of forest and shrubland ecosystems, and fish and wildlife habitat. Climate change may impact the timing and supply of the water resources, affecting the multiple uses of this river system. (Figure source: Northwest Habitat Institute 1999).

The Columbia River Basin is one example of an area where risks, vulnerabilities, and opportunities are being jointly considered by a wide range of stakeholders and decision-makers (see Ch. 28: Adaptation). The Columbia River, which crosses the U.S.-Canada border, is the fourth largest river on the continent by volume, and it drives the production of more electricity than any other river in North America. Approximately 15% of the Columbia River Basin lies within British Columbia (Figure 10.10), but an average of 30% of the total average discharge originates from the Canadian portion of the watershed.[52] To provide flood control for the U.S. and predicted releases for hydropower generation, the Columbia River system is managed through a treaty that established a cooperative agreement between the United States and Canada to regulate the river for these two uses.[53] The basin also supports a range of other uses, such as navigation, tribal uses, irrigation, fish and wildlife habitat, recreation, and water resources for agricultural, industrial, and individual use. For all multi-use river basins, understanding the combined vulnerability of energy, water, and land use to climate change is essential to planning for water management and climate change adaptation.

A recent report projects a warmer annual, and drier summer, climate for the Northwest (Ch. 21: Northwest; Ch. 2: Our Changing Climate, Figures 2.14 and 2.15; Appendix 3: Climate Science Supplement, Figures 21 and 22),[54] potentially affecting both the timing and amounts of water availability. For example, if climate change reduces streamflow at certain times, fish and wildlife, as well as recreation, may be vulnerable.[55] Climate change stressors will also increase the vulnerability of the region's vast natural ecosystems and forests in multiple ways (see Ch. 7: Forests and Ch. 8: Ecosystems). Currently, only 30% of annual Columbia River Basin runoff can be stored in reservoirs.[56] Longer growing seasons might provide opportunities for greater agricultural production, but the projected warmer and drier summers could increase demand for water for irrigation, perhaps at the expense of other water uses due to storage limitations. Wetter winters might offset increased summer demands. However, the storage capacities of many water reservoirs with multiple purposes, including hydropower, were not designed to accommodate significant increases in winter precipitation. Regulations and operational requirements also constrain the ability to accommodate changing precipitation patterns (see Ch. 3: Water).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Because of the complexity of interactions among energy, water, and land systems, considering the complete picture of climate impacts and potential adaptations can help provide better solutions. Adaptation to climate change occurs in large part locally or regionally, and conflicting stakeholder priorities, institutional commitments, and international agreements have the potential to complicate or even compromise adaption strategies with regard to energy, water, and land resources (see also Ch. 28: Adaptation). Effective adaptation to the impacts of climate change requires a better understanding of the interactions among the energy, water, and land resource sectors. Whether managing for water availability and quality in the context of energy systems, or land restrictions, or both, an improved dialog between the scientific and decision-making communities will be necessary to evaluate tradeoffs and compromises needed to manage and understand this complex system. This will require not only integrated and quantitative analyses of the processes that underlie the climate and natural systems, but also an understanding of decision criteria and risk analyses to communicate effectively with stakeholders and decision-makers.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The authors met for a one-day face-to-face meeting, and held teleconferences approximately weekly from March through August 2012. They considered a variety of technical input documents, including a Technical Input Report prepared through an interagency process,[1] and 59 other reports submitted through the Federal Register Notice request for public input. The key messages were selected based on expert judgment, derived from the set of examples assembled to demonstrate the character and consequences of interactions among the energy, water, and land resource sectors.

Key message #1 Traceable Account

Energy, water, and land systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate change vulnerability as well as adaptation and mitigation options for different regions of the country.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report (TIR): Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment.[1] Technical input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The TIR[1] incorporates the findings of a workshop, convened by the author team, of experts and stakeholders. The TIR summarizes numerous examples of interactions between specific sectors, such as energy and water or water and land use. A synthesis of these examples provides insight into how climate change impacts the interactions between these sectors.

The TIR[1] shows that the character and significance of interactions among the energy, water, and land resource sectors vary regionally. Additionally, the influence of impacts on one sector for the other sectors will depend on the specific impacts involved. Climate change impacts will affect the interactions among sectors, but this may not occur in all circumstances.

The key message is supported by the National Climate Assessment Climate Scenarios (for example, Kunkel et al. 2013[54]). Many of the historic trends included in the Climate Scenarios are based on data assembled by the Cooperative Observer Network of the National Weather Service (http://www.nws.noaa.gov/om/coop/). Regional climate outlooks are based on the appropriate regional chapter.

The Texas drought of 2011 and 2012 provides a clear example of cascading impacts through interactions among the energy, water, and land resource sectors.[3,4,5,7,8,9] The U.S. Drought Monitor (http://droughtmonitor.unl.edu/) provides relevant historical data. Evidence also includes articles appearing in the public press[11] and Internet media.[6]

New information and remaining uncertainties

The Texas drought of 2011 and 2012 demonstrates the occurrence of cascading impacts involving the energy, land, and water sectors; however, the Texas example cannot be generalized to all parts of the country or to all impacts of climate change (for example, see Chapter 3 for flooding and energy system impacts). The Technical Input Report[1] provides numerous additional examples and a general description of interactions that underlie cascading impacts between these resource sectors.

There are no major uncertainties regarding this key message. There are major uncertainties, however, in the magnitude of impacts in how decisions in one sector might affect another. The intensity of interactions will be difficult to assess under climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high**. The primary limitation on the confidence assigned to this key message is with respect to its generality. The degree of interactions among the energy, water, and land sectors varies regionally as does the character and intensity of climate change.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

The dependence of energy systems on land and water supplies will influence the development of these systems and options for reducing greenhouse gas emissions, as well as their climate change vulnerability.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report (TIR): Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment.[1] Technical input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Synthesis and Assessment Product 2.1 of the Climate Change Science Program,[22] which informed the prior National Climate Assessment,[57] describes relationships among different future mixtures of energy sources, and associated radiative forcing of climate change, as a context for evaluating emissions mitigation options.

Energy, water, and land linkages represent constraints, risks, and opportunities for private/public planning and investment decisions. There are evolving water and land requirements for four energy technologies: natural gas from shale,[13] solar power,[34] biofuels,[38,39] and carbon dioxide capture and storage (CCS).[47] Each of these four technologies could contribute to reducing U.S. emissions of greenhouse gases. These technologies illustrate energy, water, and land linkages and other complexities for the design, planning, and deployment of our energy future.

Evidence for energy production and use are derived from U.S. government reports.[58] The contributions of hydraulic fracturing to natural gas production are based on a brief article by the Energy Information Administration[13] and a primer by the U.S. Department of Energy.[28] Information about water and energy demands for utility-scale solar power facilities is derived from two major DOE reports.[34,59] Distribution of U.S. solar energy resources is from Web-based products of the National Renewable Energy Laboratory (http://www.nrel.gov/gis/). On biofuels, there are government data on the scale of biomass-based energy,[13] and studies on water and land requirements and other social and environmental aspects.[38,39]

New information and remaining uncertainties

There are no major uncertainties regarding this key message. Progress in development and deployment of the energy technologies described has tended to follow a pattern: potential constraints arise because of dependence on water and land resources, but then these constraints motivate advances in technology to reduced dependence or result in adjustments of societal priorities. There are uncertainties in how energy systems' dependence on water will be limited by other resources, such as land; uncertainties about the effects on emissions and the development and deployment of future energy technologies; and uncertainties about the impacts of climate change on energy systems.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high**. The primary limitation on confidence assigned to this key message is with respect to its generality and dependence on technological advances. Energy technology development has the potential to reduce water and land requirements, and to reduce vulnerability to climate change impacts. It is difficult to forecast success in this regard for technologies such as CCS that are still in early phases of development.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is challenging, but can improve the identification and evaluation of options for reducing climate change impacts.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report (TIR): Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment.[1] Technical input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

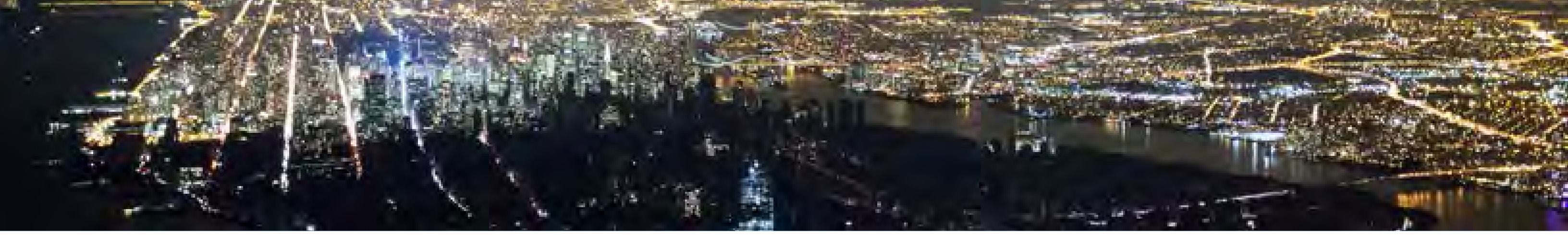
Interactions among energy, water, and land resource sectors can lead to stakeholder concerns that shape options for reducing vulnerability and thus for adapting to climate change. The Columbia River System provides a good example of an area where risks, vulnerabilities, and opportunities are being jointly considered.[55,56] The 2011 Mississippi basin flooding, which shut down substations, provides another example of the interactions of energy, water, and land systems (Ch. 3: Water). For all multi-use river basins, understanding the combined vulnerability of energy, water, and land use to climate change is essential to planning for water management and climate change adaptation.

New information and remaining uncertainties

There are no major uncertainties regarding this key message; however, it is highly uncertain the extent to which local, state and national policies will impact options to reduce vulnerability to climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high**. The primary limitation on confidence assigned to this key message is with respect to the explicit knowledge of the unique characteristics of each region with regards to impacts of climate change on energy, water, land, and the interactions among these sectors.



Climate Change Impacts in the United States

CHAPTER 11
URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY

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On the Web: http://nca2014.globalchange.gov/report/sectors/urban

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

11

URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY

KEY MESSAGES

1. **Climate change and its impacts threaten the well-being of urban residents in all U.S. regions. Essential infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts. The nation's economy, security, and culture all depend on the resilience of urban infrastructure systems.**
2. **In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.**
3. **Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.**
4. **City government agencies and organizations have started adaptation plans that focus on infrastructure systems and public health. To be successful, these adaptation efforts require cooperative private sector and governmental activities, but institutions face many barriers to implementing coordinated efforts.**

Climate change poses a series of interrelated challenges to the country's most densely populated places: its cities. The United States is highly urbanized, with about 80% of its population living in cities and metropolitan areas. Many cities depend on infrastructure, like water and sewage systems, roads, bridges, and power plants, that is aging and in need of repair or replacement. Rising sea levels, storm surges, heat waves, and extreme weather events will compound these issues, stressing or even overwhelming these essential services.

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Heavy snowfalls during winter storms affect transportation systems and other urban infrastructure.

Cities have become early responders to climate change challenges and opportunities due to two simple facts: first, urban areas have large and growing populations that are vulnerable for many reasons to climate variability and change; and second, cities depend on extensive infrastructure systems and the resources that support them. These systems are often connected to rural locations at great distances from urban centers.

The term infrastructure is used broadly and includes systems and assets that are essential for national and economic security, national public health or safety, or to the overall well-being of residents. These include energy, water and wastewater, transportation, public health, banking and finance, telecommunications, food and agriculture, and information technology, among others.

Urban dwellers are particularly vulnerable to disruptions in essential infrastructure services, in part because many of these infrastructure systems are reliant on each other. For example, electricity is essential to multiple systems, and a failure in the electrical grid can affect water treatment, transportation services, and public health. These infrastructure systems – lifelines to millions – will continue to be affected by various climate-related events and processes.

As climate change impacts increase, climate-related events will have large consequences for significant numbers of people living in cities or suburbs. Also at risk from climate change are historic properties and sites as well as cultural resources and archeological sites. Vulnerability assessments and adaptation planning efforts could also include these irreplaceable resources. Changing conditions also create opportunities and challenges for urban climate adaptation (Ch. 28: Adaptation), and many cities have begun planning to address these changes.

Key Message 1: Urbanization and Infrastructure Systems

Climate change and its impacts threaten the well-being of urban residents in all U.S. regions. Essential infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts. The nation's economy, security, and culture all depend on the resilience of urban infrastructure systems.

Direct and interacting effects of climate change will expose people who live in cities across the United States to multiple threats. Climate changes affect the built, natural, and social infrastructure of cities, from storm drains to urban waterways to the capacity of emergency responders. Climate change increases the risk, frequency, and intensity of certain extreme events like intense heat waves, heavy downpours, flooding from intense precipitation and coastal storm surges, and disease incidence related to temperature and precipitation changes. The vulnerability of urban dwellers multiplies when the effects of climate change interact with pre-existing urban stressors, such as deteriorating infrastructure, areas of intense poverty, and high population density.

Three fundamental conditions define the key connections among urban systems, residents, and infrastructure.[1,2] First, cities are dynamic, and are constantly being built and rebuilt through cycles of investment and innovation. Second, infrastructure in many cities has exceeded its design life and continues to age, resulting in an increasingly fragile system. At both local and national levels, infrastructure requires ongoing maintenance and investment to avoid a decline in service. Third, urban areas present tremendous social challenges, given widely divergent socioeconomic conditions and dynamic residence patterns that vary in different parts of each city. Heightened vulnerability of coastal cities and other metropolitan areas that are subject to storm surge, flooding, and other extreme weather or climate events will exacerbate impacts on populations and infrastructure systems.

Approximately 245 million people live in U.S. urban areas, a number expected to grow to 364 million by 2050.[3] Paradoxically, as the economy and population of urban areas grew in past decades, the built infrastructure within cities and connected to cities deteriorated, becoming increasingly fragile and deficient.[1,2] Existing built infrastructure (such as buildings, energy, transportation, water, and sanitation systems) is expected to become more stressed in the next decades – especially when the impacts of climate change are added to the equation.[4] As infrastructure is highly interdependent, failure in particular sectors is expected to have cascading effects on most aspects of affected urban economies. Further expansion of the U.S. urban landscape into suburban and exurban spaces is expected, and new climate adaptation and resiliency plans will need to account for this (Ch. 28: Adaptation).[5] Significant increases in the costs of infrastructure investments also are expected as population density becomes more diffuse.[6]

The vulnerability of different urban populations to hazards and risks associated with climate change depends on three characteristics: their exposure to particular stressors, their sensitivity to impacts, and their ability to adapt to changing conditions.[8,9] Many major U.S. metropolitan areas, for example, are located on or near the coast and face higher exposure to particular climate impacts like sea level rise and storm surge, and thus may face complex and costly adaptation demands (Ch. 25: Coasts; Ch. 28: Adaptation). But as people begin to respond to new


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Coastal cities are vulnerable to sea level rise, storm surge, and related impacts.

Blackout in New York and New Jersey after Hurricane Sandy

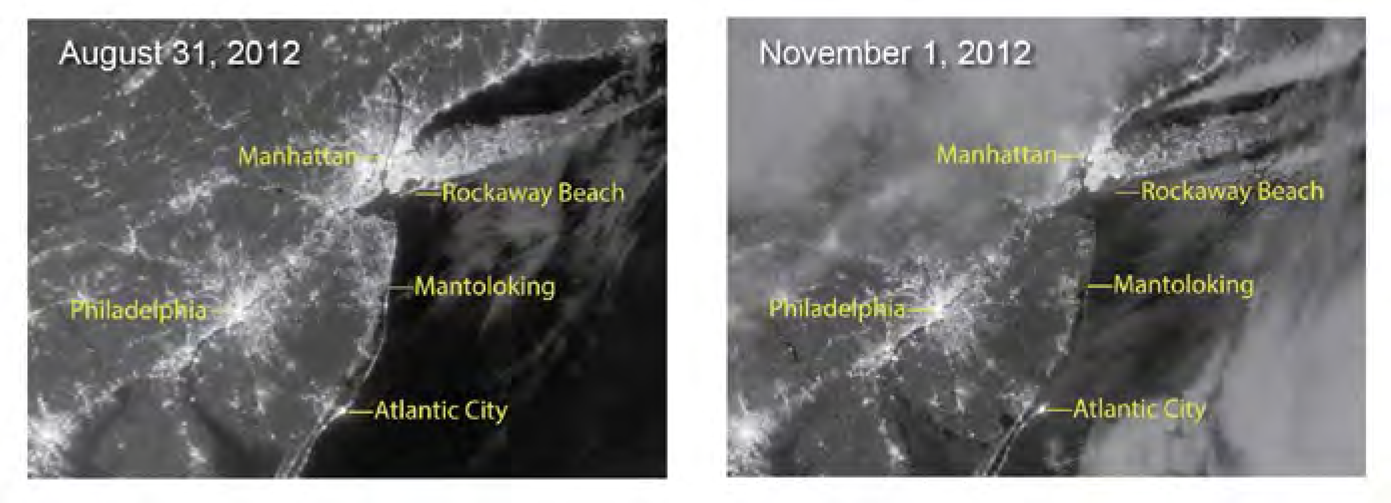

Figure 11.1. Extreme weather events can affect multiple systems that provide services for millions of people in urban settings. The satellite images depict city lights on a normal night (left) and immediately following Hurricane Sandy (right). Approximately five million customers in the New York metropolitan region lost power. (Figure source: NASA Earth Observatory[7]).

information about climate change through the urban development process, social and infrastructure vulnerabilities can be altered.[10] For example, the City of New York conducted a comprehensive review of select building and construction codes and standards in response to increased climate change risk in order to identify adjustments that could be made to increase climate resilience. Climate change stressors will bundle with other socioeconomic and engineering stressors already connected to urban and infrastructure systems.[1]

Key Message 2: Essential Services are Interdependent

In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

Urban areas rely on links to multiple jurisdictions through a complex set of infrastructure systems.[11] For example, cities depend on other areas for supplies of food, materials, water, energy, and other inputs, and surrounding areas are destinations for products, services, and wastes from cities. If infrastructure and other connections among source areas and cities are disrupted by climate change, then the dependent urban area also will be affected.[12] Moreover, the economic base of an urban area depends on regional comparative advantage; therefore, if competitors, markets, and/or trade flows are affected by climate change, a particular urban area is also affected.[2]

Urban vulnerabilities to climate change impacts are directly related to clusters of supporting resources and infrastructures located in other regions. For example, about half of the nation's oil refineries are located in only four states.[13] Experience over the past decade with major infrastructure disruptions, such as the 2011 San Diego blackout, the 2003 Northeast blackout, and Hurricane Irene in 2011, has shown that the greatest losses from disruptive events may be distant from where damages started.[2] In another example, Hurricane


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A failure of the electrical grid can affect everything from water treatment to public health.

Katrina disrupted oil terminal operations in southern Louisiana, not because of direct damage to port facilities, but because workers could not reach work locations through surface transportation routes and could not be housed locally because of disruption to potable water supplies, housing, and food shipments.[14]

Although infrastructures and urban systems are often considered individually – for example, transportation or water supply or wastewater/drainage – they are usually highly interactive and interdependent.[15]

Urban Support Systems are Interconnected

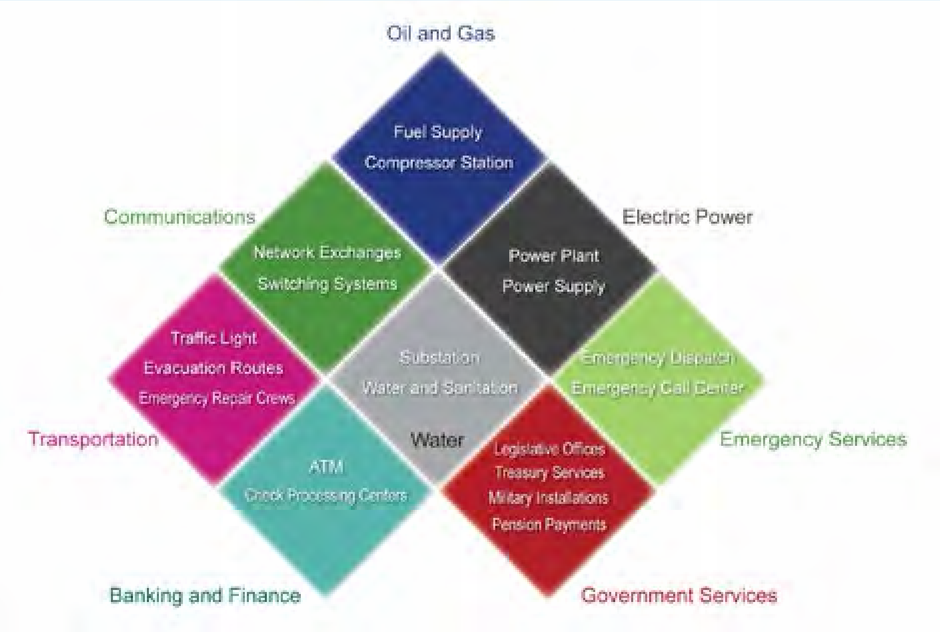

Figure 11.2. In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other systems. When power supplies that serve urban areas are interrupted after a major weather event, for example, public health, transportation, and banking systems may all be affected. This schematic drawing illustrates some of these connections. (Figure source: adapted from Wilbanks et al. 2012[2]).

Such interdependencies can lead to cascading disruptions throughout urban infrastructures. These disruptions, in turn, can result in unexpected impacts on communication, water, and public health sectors, at least in the short term. On August 8, 2007, New York City experienced an intense rainfall and thunderstorm event during the morning commute, where between 1.4 and 3.5 inches of rain fell within two hours.[16] The event started a cascade of transit system failures – eventually stranding 2.5 million riders, shutting down much of the subway system, and severely disrupting the city's bus system.[16,17] The storm's impact was unprecedented and, coupled with two other major system disruptions that occurred in 2004 and 2007, became the impetus for a full-scale assessment and review of transit procedures and policy in response to climate change.[16,17,18]

In August 2003, an electric power blackout that caused 50 million people in the U.S. Northeast and Midwest and Ontario, Canada, to lose electric power further illustrates the interdependencies of major infrastructure systems. The blackout caused significant indirect damage, such as shutdowns of water treatment plants and pumping stations. Other impacts included interruptions in communication systems for air travel and control systems for oil refineries. At a more local level, the lack of air conditioning and elevator access meant many urban residents were stranded in over-heating high-rise apartments. Similar cascading impacts have been observed from extreme weather events such as Hurricanes Katrina and Irene.[2] In fact, as urban infrastructures become more interconnected and more complex, the likelihood of large-scale cascading impacts will increase as risks to infrastructure increase.[19]

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Storm surges reach farther inland as they ride on top of sea levels that are higher due to warming.

HURRICANE SANDY: URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY


Courtesy of NOAA

Sandy made landfall on the New Jersey shore just south of Atlantic City on October 29, 2012, and became one of the most damaging storms to strike the continental United States. Sandy affected cities throughout the Atlantic seaboard, extending across the eastern United States to Chicago, Illinois, where it generated 20-foot waves on Lake Michigan and flooded the city's Lake Shore Drive. The storm's strength and resulting impact has been correlated with Atlantic Ocean water temperatures near the coast that were roughly 5°F above normal, and with sea level rise along the region's coastline as a result of a warming climate.

Sandy caused significant loss of life as well as tremendous destruction of property and critical infrastructure. It disrupted daily life for millions of coastal zone residents across the New York-New Jersey metropolitan area, despite this being one of the best disaster-prepared coastal regions in the country. The death toll from Sandy in the metropolitan region exceeded 100, and the damage was estimated to be at least $65 billion.[20,21] At its peak, the storm cut electrical power to more than 8.5 million customers.[21]

The death and injury, physical devastation, multi-day power, heat, and water outages, gasoline shortages, and cascade of problems from Sandy's impact reveal what happens when the complex, integrated systems upon which urban life depends are stressed and fail. One example is what occurred after a Consolidated Edison electricity distribution substation in lower Manhattan ceased operation at approximately 9 PM Monday evening, when its flood protection barrier (designed to be 1.5 feet above the 10-foot storm surge of record) was overtopped by Sandy's 14-foot storm surge. As the substation stopped functioning, it immediately caused a system-wide loss of power for more than 200,000 customers. Residents in numerous high-rise apartment buildings were left without heat and lights, and also without elevator service and water (which must be pumped to upper floors).

Sandy also highlighted the vast differences in vulnerabilities across the extended metropolitan region. Communities and neighborhoods on the coast were most vulnerable to the physical impact of the record storm surge. Many low- to moderate-income residents live in these areas and suffered damage to or loss of their homes, leaving tens of thousands of people displaced or homeless. As a specific sub-population, the elderly and infirm were highly vulnerable, especially those living in the coastal evacuation zone and those on upper floors of apartment buildings left without elevator service. These individuals had limited adaptive capacity because they could not easily leave their residences.

Even with the extensive devastation, the effects of the storm would have been far worse if local climate resilience strategies had not been in place. For example, the City of New York and the Metropolitan Transportation Authority worked aggressively to protect life and property by stopping the operation of the city's subway before the storm hit and moving the train cars out of low-lying, flood-prone areas. At the height of the storm surge, all seven of the city's East River subway tunnels flooded. Catastrophic loss of life would have resulted if there had been subway trains operating in the tunnels when the storm struck. The storm also fostered vigorous debate among local and state politicians, other decision-makers, and stakeholders about how best to prepare the region for future storms. Planning is especially important given the expectation of increases in flood frequency resulting from more numerous extreme precipitation events and riverine and street level flooding, and coastal storm surge flooding associated with accelerated sea level rise and more intense (yet not necessarily more numerous) tropical storms.

Key Message 3: Social Vulnerability and Human Well-Being

Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

"Social vulnerability" describes characteristics of populations that influence their capacity to prepare for, respond to, and recover from hazards and disasters.[22,23,24] Social vulnerability also refers to the sensitivity of a population to climate change impacts and how different people or groups are more or less vulnerable to those impacts.[25] Those characteristics that most often influence differential impacts include socioeconomic status (wealth or poverty), age, gender, special needs, race, and ethnicity.[26] Further, inequalities reflecting differences in gender, age, wealth, class, ethnicity, health, and disabilities also influence coping and adaptive capacity, especially to climate change and climate-sensitive hazards.[27]

The urban elderly are particularly sensitive to heat waves. They are often physically frail, have limited financial resources, and live in relative isolation in their apartments. They may not have adequate cooling (or heating), or may be unable to temporarily relocate to cooling stations. This combination led to a significant number of elderly deaths during the 1995 Chicago heat wave.[28] Similarly, the impacts of Hurricane Katrina in New Orleans illustrated profound differences based on race, gender, and class where these social inequalities strongly influenced the capacity of residents to prepare for and respond to the events.[29] It is difficult to assess the specific nature of vulnerability for particular groups of people. Urban areas are not homogeneous in terms of the social structures that influence inequalities. Also, the nature of the vulnerability is context specific, with both temporal and geographic determinants, and these also vary between and within urban areas.

Key Message 4: Trends in Urban Adaptation – Lessons from Current Adopters

City government agencies and organizations have started adaptation plans that focus on infrastructure systems and public health. To be successful, these adaptation efforts require cooperative private sector and governmental activities, but institutions face many barriers to implementing coordinated efforts.

City preparation efforts for climate change include planning for ways in which the infrastructure systems and buildings, ecosystem and municipal services, and residents will be affected. In the first large-scale analysis of U.S. cities, a 2011 survey showed that 58% of respondents are moving forward on climate adaptation (Ch. 28: Adaptation), defined as any activity to address impacts that climate change could have on a community. Cities are engaged in activities ranging from education and outreach to assessment, planning, and implementation, with 48% reporting that they are in the preliminary planning and discussion phases.[30]

Cities either develop separate strategic adaptation plans[30,32] or integrate adaptation into community or general plans (as have Seattle, Washington; Portland, Oregon; Berkeley, California; and Homer, Alaska) (Ch. 28: Adaptation).[1] Some climate action plans target certain sectors like critical infrastructure,[24,33] and these have been effective in diverse contexts ranging from hazard mitigation and public-health planning to coastal-zone management and economic development.

Cities have employed several strategies for managing adaptation efforts. For example, some approaches to climate adaptation planning require both intra- and inter-governmental agency and department coordination ("New York City Climate Action") (Ch. 28: Adaptation). As a result, many cities focus on sharing information and examining what aspects of government operations will be affected by climate change impacts in order to gain support from municipal agency stakeholders and other local officials.[34] Some cities also have shared climate change action experiences, both within the United States and internationally, as is the case with ongoing communication between decision-makers in New York City and London, England.

National, state, and local policies play an important role in fostering and sustaining adaptation. There are no national regulations specifically designed to promote urban adaptation. However, existing federal policies, like the National Historic Preservation Act and National Environmental Policy Act – particularly through its impact assessment provision and evaluation criteria process – can provide incentives for adaptation strategies for managing federal property in urban areas.[1,35] In addition, recent activities of federal agencies focused on promoting adaptation and resilience have been developed in partnership with cities like Miami and New York.[36] Policies and planning measures at the local level, such as building codes, zoning regulations, land-use plans, water supply management, green infrastructure initiatives, health care planning, and disaster mitigation efforts, can support adaptation.[1,2,37]

Engaging the public in adaptation planning and implementation has helped to inform and educate the community at large

New York City and Sea Level Rise

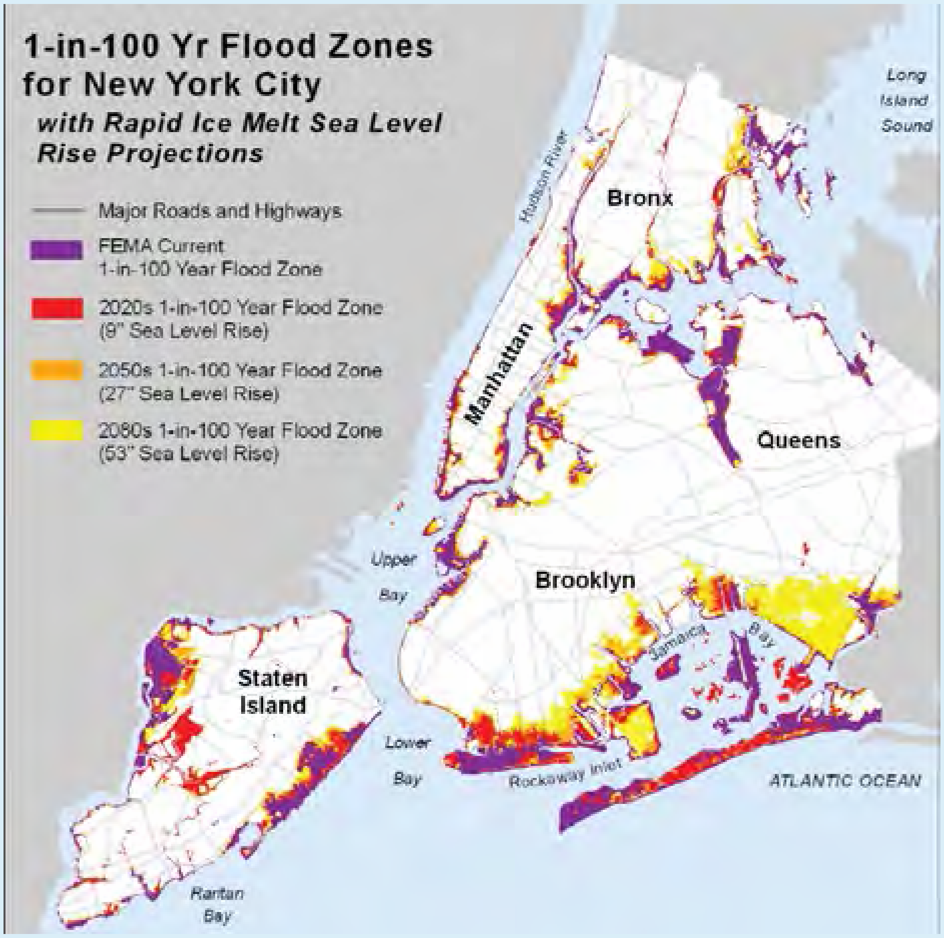

Figure 11.3. Map shows areas in New York's five boroughs that are projected to face increased flooding over the next 70 years, assuming an increased rate of sea level rise from the past century's average. As sea level rises, storm surges reach farther inland. Map does not represent precise flood boundaries, but illustrates projected increases in areas flooded under various sea level rise scenarios. (Figure source: New York City Panel on Climate Change 2013[31]).

about climate change, while ensuring that information and ideas flow back to policymakers.[38] Engagement can also help in identifying vulnerable populations[39] and in mobilizing people to encourage policy changes and take individual actions to reduce and adapt to climate change.[40] For instance, the Cambridge Climate Emergency Congress selected a demographically diverse group of resident delegates and engaged them in a deliberative process intended to express preferences and generate recommendations to inform climate action.[41] In addition, the Boston Climate Action Leadership Committee was initiated by the Mayor's office with the expectation that they would rely on public consultation to develop recommendations for updating the city's climate action plan.[42]

There are many barriers to action at the city level. Proactive adaptation efforts require that anticipated climate changes and impacts are evaluated and addressed in the course of the planning process (Ch. 26: Decision Support; Ch. 28: Adaptation).[43] This means that climate projections and impact assessment data must be available, but most U.S. cities are unable to access suitable data or perform desired analyses.[36] To address technical aspects of adaptation, cities are promoting cooperation with local experts, such as the New York City Panel on Climate Change, which brings together experts from academia and the public and private sectors to consider how the region's critical infrastructure will be affected by, and can be protected from, future climate change.[10,44] A further illustration comes from Chicago, where multi-departmental groups are focusing on specific areas identified in Chicago's Climate Action Plan.[45]

Private sector involvement can be influential in promoting city-level adaptation (Ch. 28: Adaptation). Many utilities, for example, have asset management programs that address risk and vulnerabilities, which could also serve to address climate change. Yet to date there are limited examples of private sector interests working cooperatively with governments to limit risk. Instances where cooperation has taken place include property insurance companies[1,46] and engineering firms that provide consulting services to cities. For example, firms providing infrastructure system plans have begun to account for projected changes in precipitation in their projects.[47] With city and regional infrastructure systems, recent attention has focused on the potential role of private sector-generated smart technologies to improve early warning of extreme precipitation and heat waves, as well as establishing information systems that can inform local decision-makers about the status and efficiency of infrastructure.[46,48]

Uncertainty, in both the climate system and modeling techniques, is often viewed as a barrier to adaptation action (Ch. 28: Adaptation).[49] Urban and infrastructure managers, however, recognize that understanding of sources and magnitude of future uncertainty will continue to be refined,[39] and that an incremental and flexible approach to planning that draws on both structural and nonstructural measures is prudent.[44,46,50] Gaining the commitment and support of local elected officials for adaptation planning and implementation is another important challenge.[30] A compounding problem is that cities and city administrators face a wide range of other stressors demanding their attention, and have limited financial resources (see "Advancing Climate Adaptation in a Metropolitan Region").[46]

Integrating climate change action in everyday city and infrastructure operations and governance (referred to as "mainstreaming") is an important planning and implementation tool for advancing adaptation in cities (Ch. 28: Adaptation).[44,46] By integrating climate change considerations into daily operations, these efforts can forestall the need to develop a new and isolated set of climate change-specific policies or procedures.[39] This strategy enables cities and other government agencies to take advantage of existing funding sources and programs, and achieve co-benefits in areas such as sustainability, public health, economic development, disaster preparedness, and environmental justice. Pursuing low-cost, no-regrets options is a particularly attractive short-term strategy for many cities.[39,46]

Over the long term, responses to severe climate change impacts, such as sea level rise and greater frequency and intensity of other climate-related hazards, are of a scale and complexity that will likely require major expenditures and structural changes,[1,46] especially in urban areas. When major infrastructure decisions must be made in order to protect human lives and urban assets, cities need access to the best available science, decision support tools, funding, and guidance. The Federal Government is seen by local officials to have an important role here by providing adaptation leadership and financial and technical resources, and by conducting and disseminating research (Ch. 28: Adaptation).[36,39,46]

ADVANCING CLIMATE ADAPTATION IN A METROPOLITAN REGION

Coordinating efforts across many jurisdictional boundaries is a major challenge for adaptation planning and practice in extended metropolitan regions and associated regional systems (Ch. 28: Adaptation). Regional government institutions may be well suited to address this challenge, as they cover a larger geographic scope than individual cities, and have potential to coordinate the efforts of multiple jurisdictions.[1] California already requires metropolitan planning organizations to prepare Sustainable Communities Strategies (SCS) as part of the Regional Transportation Plan process.[51] While its focus is on reducing emissions, SCS plans prepared to date have also introduced topics related to climate change impacts and adaptation.[52] Examples of climate change vulnerabilities that could benefit from a regional perspective include water shortages, transportation infrastructure maintenance, loss of native plant and animal species, and energy demand.

NEW YORK CITY CLIMATE ACTION

New York City leaders recognized that climate change represents a serious threat to critical infrastructure and responded with a comprehensive program to address climate change impacts and increase resilience.[1,2] The 2010 "Climate Change Adaptation in New York City: Building a Risk Management Response" report was prepared by the New York City Panel on Climate Change as a part of the city's long-term sustainability plan.[10] Major components of the process and program include:

- establishing multiple participatory processes to obtain broad public input, including a Climate Change Adaptation Task Force that included private and public stakeholders;[46]
- forming an expert technical advisory body, the New York City Panel on Climate Change (NPCC), to support the Task Force;
- developing a Climate Change Assessment and Action Plan that helps improve responses to present-day climate variability as well as projected future conditions;
- defining "Climate Protection Levels" to address the effectiveness of current regulations and design standards to respond to climate change impacts; and
- producing adaptation assessment guidelines that recognize the need for flexibility to reassess and adjust strategies over time. The guidelines include a risk matrix and prioritization framework intended to become integral parts of ongoing risk management and agency operations.

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11: URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

In developing key messages, the report author team engaged in multiple technical discussions via teleconference. A consensus process was used to determine the final set of key messages, which are supported by extensive evidence documented in two Technical Report Inputs to the National Climate Assessment on urban systems, infrastructure, and vulnerability: 1) *Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the U.S. Department of Energy in Support of the National Climate Assessment*,[2] and 2) *U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues*.[1] Other Technical Input reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

KEY MESSAGE 1 TRACEABLE ACCOUNT

Climate change and its impacts threaten the well-being of urban residents in all U.S. regions. Essential infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts. The nation's economy, security, and culture all depend on the resilience of urban infrastructure systems.

Description of evidence base

Recent studies have reported that population and economic growth have made urban infrastructure more fragile and deficient,[1,2] with work projecting increased stresses due to climate change[4] and increased costs of adaptation plans due to more extensive urban development.[6] Additionally, a few publications have assessed the main drivers of vulnerability[8,9] and the effects of the amalgamation of climate change stresses with other urban and infrastructure stressors.[1]

New information and remaining uncertainties

Given that population trends and infrastructure assessments are well established and documented, the largest uncertainties are associated with the rate and extent of potential climate change.

Since the 2009 National Climate Assessment,[53] recent publications have explored the driving factors of vulnerability in urban systems[8,9] and the effects of the combined effect of climate change and existing urban stressors.[1]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that climate change and its impacts threaten the well-being of urban residents in all regions of the U.S.

Given the evidence base and remaining uncertainties, confidence is **very high** that essential local and regional infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts.

Confidence Level	
Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE 2 TRACEABLE ACCOUNT

In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

Description of evidence base

The interconnections among urban systems and infrastructures have been noted in the past,[19] with recent work expanding on this principle to assess the risks this interconnectivity poses. One study[15] explored the misconception of independent systems, and stressed instead the interactive and interdependent nature of systems. The effects of climate change on one system ultimately affect systems that are dependent upon it.[12] One of the foundational Technical Input Reports examined the economic effects from climate change and how they will affect urban areas.[2] Noted examples of this interconnectivity can be found in a number of publications concerning Hurricane Katrina,[14] intense weather in New York City,[16,17] and the vulnerability of U.S. oil refineries and electric power plants.[2,13]

New information and remaining uncertainties

Recent work has delved deeper into the interconnectivity of urban systems and infrastructure,[2,12] and has expressed the importance of understanding these interactions when adapting to climate change.

The extensive number of infrastructure assessments has resulted in system interdependencies and cascade effects being well documented. Therefore, the most significant uncertainties are associated with the rate and extent of potential climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that in urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

KEY MESSAGE 3 TRACEABLE ACCOUNT

Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

Description of evidence base

The topic of social vulnerability has been extensively studied,[22,23,24] with some work detailing the social characteristics that are the most influential.[26] More recent work has addressed the vulnerability of populations to climate change[25] and how social inequalities influence capacity to adapt to climate change.[27] Some empirical studies of U.S. urban areas were explored concerning these issues.[9]

New information and remaining uncertainties

Given that population trends and socioeconomic factors associated with vulnerability and adaptive capacity are well established and documented, the largest uncertainties are associated with the rate and extent of potential climate change.

Recent work has addressed the social vulnerabilities to climate change at a more detailed level than in the past,[23,25] providing information on the constraints that social vulnerabilities can have on climate change adaptation.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that the climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

KEY MESSAGE 4 TRACEABLE ACCOUNT

City government agencies and organizations have started adaptation plans that focus on infrastructure systems and public health. To be successful, these adaptation efforts require cooperative private sector and governmental activities, but institutions face many barriers to implementing coordinated efforts.

Description of evidence base

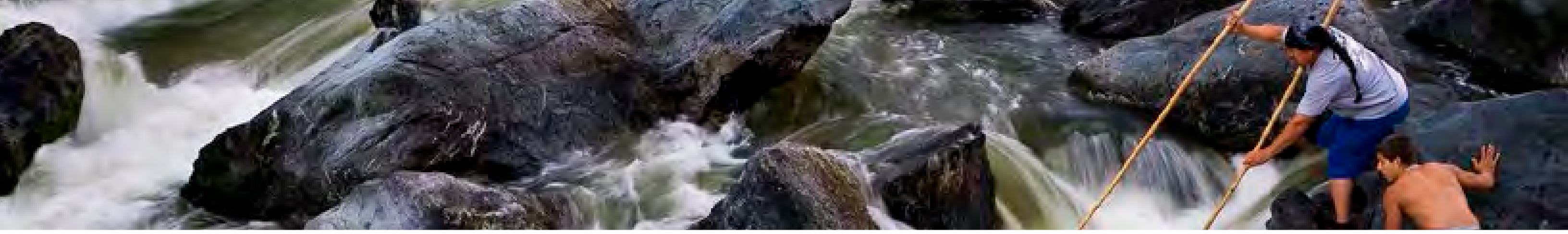
Urban adaptation is already underway with a number of cities developing plans at the city[30,32,33] and state levels,[30] with some integrating adaptation into community plans[1] and sharing information and assessing potential impacts.[34] Some recent publications have explored how incentives and administrative and financial support can benefit climate adaptation through policy planning at the local level[1,2,37] and by engaging the public.[38,39,40] Barriers exist that can hinder the adaptation process, which has been demonstrated through publications assessing the availability of scientific data[30,36] that is integral to the evaluation and planning process,[43] uncertainty in the climate system and modeling techniques,[49] and the challenges of gaining support and commitment from local officials.[30,46]

New information and remaining uncertainties

Besides uncertainties associated with the rate and extent of potential climate change, uncertainties emerge from the fact that, to date, there have been few extended case studies examining how U.S. cities are responding to climate change (<10 studies). Furthermore, only one large-scale survey of U.S. cites has been conducted for which results have been published and widely available.[30]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that city government agencies and organizations have started urban adaptation efforts that focus on infrastructure systems and public health.



Climate Change Impacts in the United States

CHAPTER 12

INDIGENOUS PEOPLES,
LAND, AND RESOURCES

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

12 INDIGENOUS PEOPLES,
LAND, AND RESOURCES

Key Messages

1. **Observed and future impacts from climate change threaten Native Peoples' access to traditional foods such as fish, game, and wild and cultivated crops, which have provided sustenance as well as cultural, economic, medicinal, and community health for generations.**
2. **A significant decrease in water quality and quantity due to a variety of factors, including climate change, is affecting drinking water, food, and cultures. Native communities' vulnerabilities and limited capacity to adapt to water-related challenges are exacerbated by historical and contemporary government policies and poor socioeconomic conditions.**
3. **Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and loss to settlements, food insecurity, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.**
4. **Alaska Native communities are increasingly exposed to health and livelihood hazards from increasing temperatures and thawing permafrost, which are damaging critical infrastructure, adding to other stressors on traditional lifestyles.**
5. **Climate change related impacts are forcing relocation of tribal and indigenous communities, especially in coastal locations. These relocations, and the lack of governance mechanisms or funding to support them, are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.**

> *We humbly ask permission from all our relatives; our elders, our families, our children, the winged and the insects, the four-legged, the swimmers, and all the plant and animal nations, to speak. Our Mother has cried out to us. She is in pain. We are called to answer her cries. Msit No'Kmaq – All my relations!*
>
> — Indigenous Prayer

The peoples, lands, and resources of indigenous communities in the United States, including Alaska and the Pacific Rim, face an array of climate change impacts and vulnerabilities that threaten many Native communities. The consequences of observed and projected climate change have and will undermine indigenous ways of life that have persisted for thousands of years. Key vulnerabilities include the loss of traditional knowledge in the face of rapidly changing ecological conditions, increased food insecurity due to reduced availability of traditional foods, changing water availability, Arctic sea ice loss, permafrost thaw, and relocation from historic homelands.[1,2,3,4]

Climate change impacts on many of the 566 federally recognized tribes and other tribal and indigenous groups in the U.S. are projected to be especially severe, since these impacts are compounded by a number of persistent social and economic problems.[6,7] The adaptive responses to multiple social and ecological challenges arising from climate impacts on indigenous communities will occur against a complex backdrop of centuries-old cultures already stressed by historical events and contemporary conditions.[8] Individual tribal responses will be grounded in the particular cultural and environmental heritage of each community, their social and geographical history, spiritual values, traditional ecological knowledge, and worldview. Furthermore, these responses will be informed by each group's distinct political and legal status, which includes the legacy of more than two centuries of non-Native social and governmental institutional arrangements, relationships, policies, and practices. Response options will be informed by the often limited economic resources available to meet these challenges, as well as these cultures' deeply ingrained relationships with the natural world.[9,10,11,12]

The history and culture of many tribes and indigenous peoples are critical to understand before assessing additional climate change impacts. Most U.S. Native populations already face adverse socioeconomic factors such as extreme poverty; substandard and inadequate housing; a lack of health and community services, food, infrastructure, transportation, and education; low employment; and high fuel costs; as well as historical and current institutional and policy issues related to Native resources.[7,11,12,13] The overwhelming driver of these adverse social indicators is pervasive poverty on reservations and in Native communities, as illustrated by an overall 28.4% poverty rate (36% for families with children) on reservations, compared with 15.3% nationally.[13] Some reservations are far worse off, with more than 60% poverty rates and, in some cases, extremely low income levels (for example, Pine Ridge Reservation has the lowest per capita income in the U.S. at $1,535 per year).[14]

These poverty levels result in problems such as: a critical housing shortage of well over two hundred thousand safe, healthy, and affordable homes;[15] a homeless rate of more than 10% on reservations;[16] a lack of electricity (more than 14% of reservation homes are without power, ten times the national average, and, on the Navajo Reservation, about 40% of homes have no electricity[17]); lack of running water in one-fifth of all reservation homes and for about one-third of people on the Navajo Reservation (compared with 1% of U.S. national households);[18,19,20] and an almost complete lack of modern telecommunications – fewer than 50% of homes have phone service, fewer than 10% of residents have Internet access, and many reservations have no cell phone reception.[21] In addition, Native populations are also vulnerable because their physical, mental, intellectual, social, and cultural well-being is traditionally tied to a close relationship with the natural world, and because of their dependence on the land and resources for basic needs such as medicine, shelter, and food.[22,23] Climate changes will exacerbate many existing barriers to providing for these human needs, and in many cases will make adaptive responses more difficult.

Of the 5.2 million American Indians and Alaska Natives registered in the U.S. Census, approximately 1.1 million live on or near reservations or Native lands, located mostly in the Northwest, Southwest, Great Plains, and Alaska. Tribal lands include approximately 56 million acres (about 3% of U.S. lands) in the 48 contiguous states and 44 million acres (about 42% of Alaska's land base) held by Alaska Native corporations.[5] Most reservations are small and often remote or isolated, with a few larger exceptions such as the Navajo Reservation in Arizona, Utah, and New Mexico, which has 175,000 residents.[5]

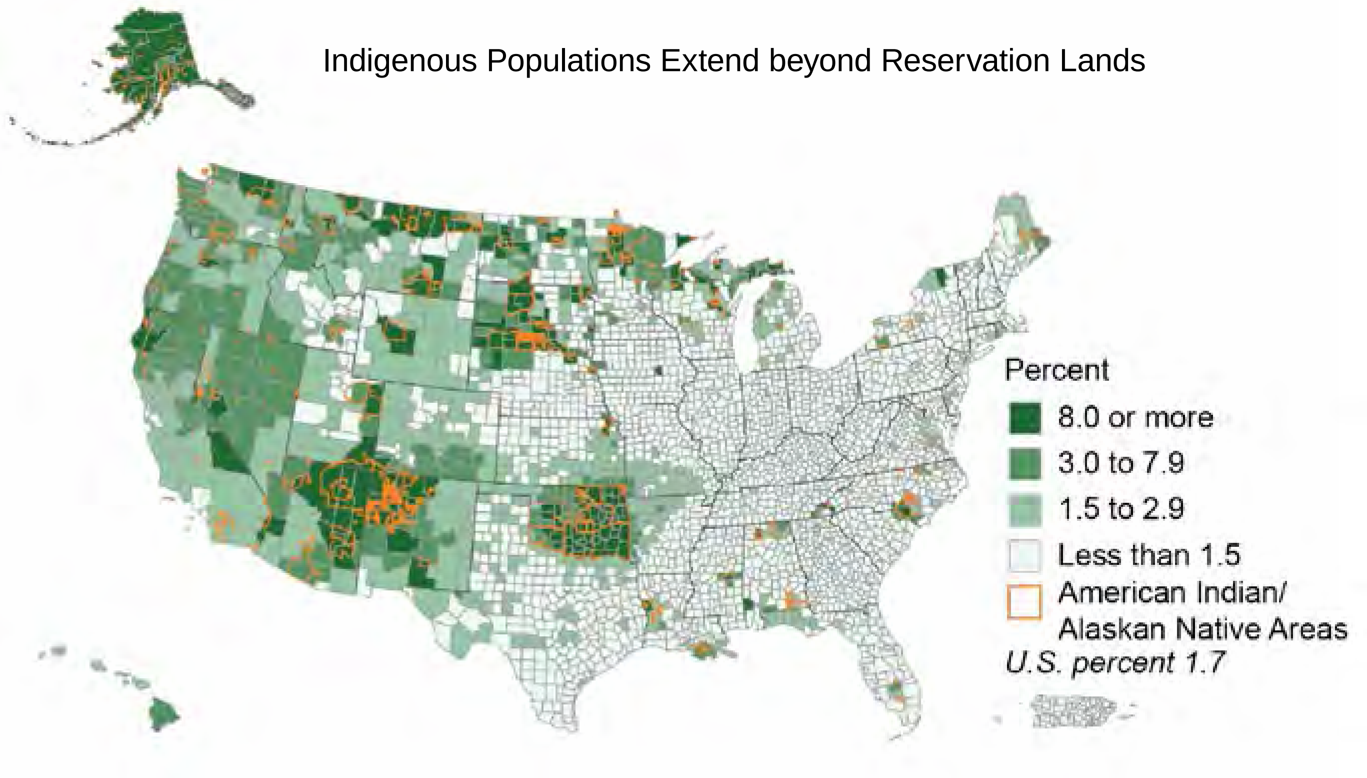

Figure 12.1. Census data show that American Indian and Alaska Native populations are concentrated around, but are not limited to, reservation lands like the Hopi and Navajo in Arizona and New Mexico, the Choctaw, Chickasaw, and Cherokee in Oklahoma, and various Sioux tribes in the Dakotas and Montana. Not depicted in this graphic is the proportion of Native Americans who live off-reservation and in and around urban centers (such as Chicago, Minneapolis, Denver, Albuquerque, and Los Angeles) yet still maintain strong family ties to their tribes, tribal lands, and cultural resources. (Figure source: Norriset al. 2012[5]).

House being built on Pine Ridge Reservation

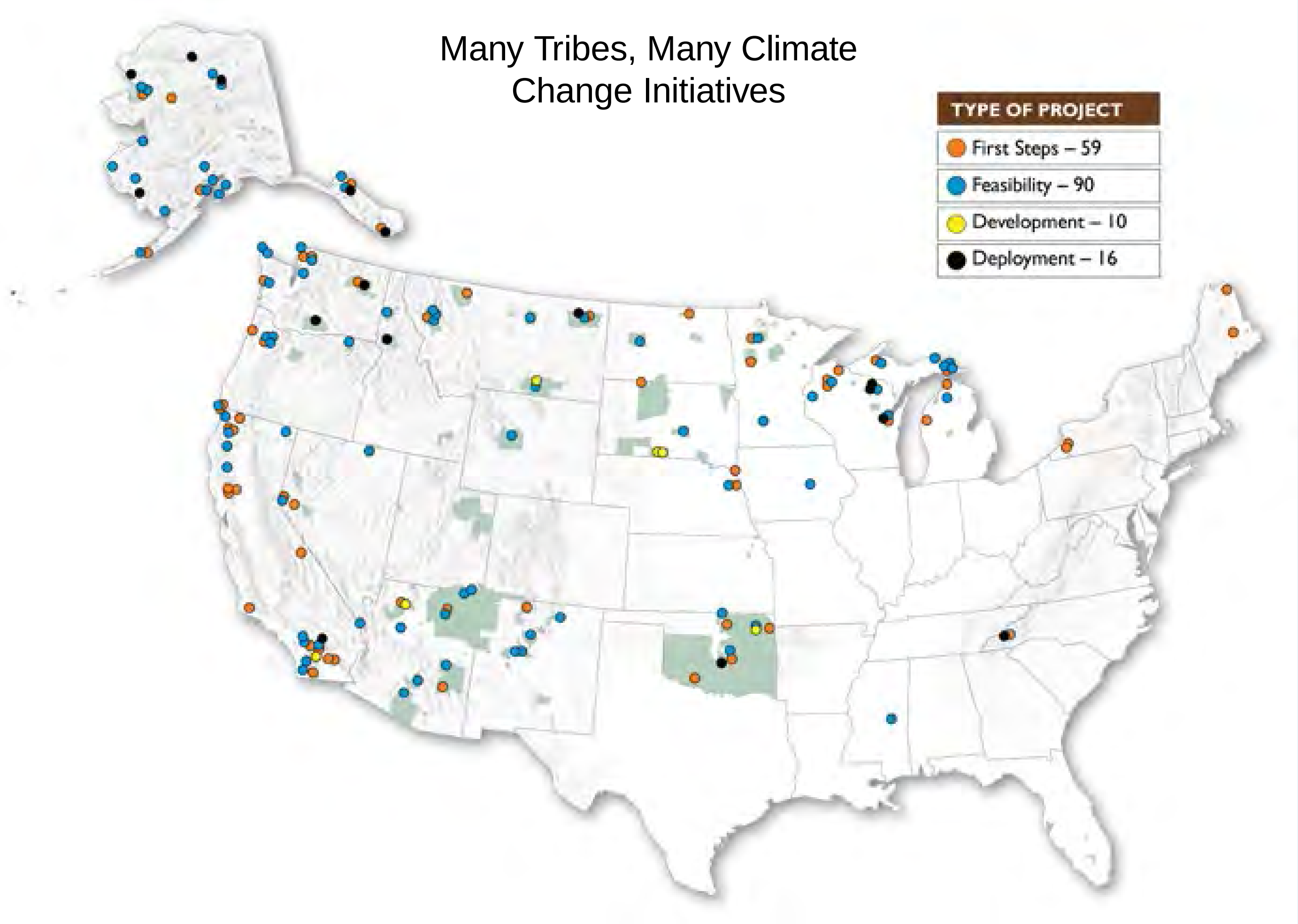

Figure 12.2. From developing biomass energy projects on the Quinault Indian Nation in Washington and tribal and intertribal wind projects in the Great Plains,[24] to energy efficiency improvement efforts on the Cherokee Indian Reservation in North Carolina and the sustainable community designs being pursued on the Lakota reservations in the Dakotas (see also Ch. 19: Great Plains),[25] tribes are investigating ways to reduce future climate changes. The map shows only those initiatives by federally recognized tribes that are funded through the Department of Energy. (Figure source: U.S. Department of Energy 2011[26]).

Native American, Alaska Native, and other indigenous communities across the U.S. share unique historical and cultural relationships with tribal or ancestral lands, significantly shaping their identities and adaptive opportunities.[11] Some climate change adaptation opportunities exist on Native lands, and traditional knowledge can enhance adaptation and sustainability strategies. In many cases, however, adaptation options are limited by poverty, lack of resources, or – for some Native communities, such as those along the northern coast of Alaska constrained by public lands or on certain low-lying Pacific Islands – because there may be no land left to call their own. Conversely, for these same reasons, Native communities – especially in the Arctic – are also increasingly working to identify new economic opportunities associated with climate change and development activities (for example, oil and gas, mining, shipping, and tourism) and to optimize employment opportunities.[1,27,28]

Climate Change and Traditional Knowledge

Indigenous traditional knowledge has emerged in national and international arenas as a source of rich information for indigenous and non-indigenous climate assessments, policies, and adaptation strategies. Working Group II of the Intergovernmental Panel on Climate Change Fourth Assessment Report recognized traditional knowledge as an important information source for improving the understanding of climate change and other changes over time, and for developing comprehensive natural resource management and climate adaptation strategies.[29]

Traditional knowledge is essential to the economic and cultural survival of indigenous peoples, and, arguably, cultures throughout the world.[30,31] Traditional knowledge has been defined as "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment."[1,12,32] From an indigenous perspective, traditional knowledge encompasses all that is known about the world around us and how to apply that knowledge in relation to those beings that share the world.[12,33] As the elders of these communities – the "knowledge keepers" – pass away, the continued existence and viability of traditional knowledge is threatened. Programs are needed to help preserve the diverse traditional teachings and employ them to strive for balance among the physical, the spiritual, emotional, and intellectual – all things that encompass "wolakota," meaning to be a complete human being.[34]

Many, if not all, indigenous resource managers believe their cultures already possess sufficient knowledge to respond to climate variation and change.[30,35] However, there are elements of traditional knowledge that are increasingly vulnerable with changing climatic conditions,[4] including cultural identities, ceremonies, and traditional ways of life.[36] The use of indigenous and traditional knowledge to address climate change issues in Indian country has been called "indigenuity" – indigenous knowledge plus ingenuity.[33]

Native cultures are directly tied to Native places and homelands, reflecting the indigenous perspective that includes the "power of place."[6,36,37] Many indigenous peoples regard all people, plants, and animals that share our world as relatives rather than resources. Language, ceremonies, cultures, practices, and food sources evolved in concert with the inhabitants, human and non-human, of specific homelands.[1,33] The wisdom and knowledge of Native people resides in songs, dances, art, language, and music that reflect these places. By regarding all things as relatives, not resources, natural laws dictate that people care for their relatives in responsible ways. *"When you say, 'my mother is in pain,' it's very different from saying 'the earth is experiencing climate change.'"*[38,39] As climate change increasingly threatens these Native places, cultural identities, and practices, documenting the impacts on traditional lifestyles would strengthen adaptive strategies.

Traditional knowledge has developed tangible and reliable methods for recording historic weather and climate variability and their impacts on native societies.[40] For example, tribal community historians (winter count keepers) on the northern Great Plains recorded pictographs on buffalo hides to remember the sequence of events that marked each year, dating back to the 1600s. These once-reliable methods are becoming increasingly more difficult to maintain and less reliable as time passes.[41]

There are recent examples, however, where traditional knowledge and western-based approaches are used together to address climate change and related impacts. For example, the Alaska Native Tribal Health Consortium chronicles climate change impacts on the landscape and on human health and also develops adaptation strategies.[1] This Consortium employs western science, traditional ecological knowledge, and a vast network of "Local Environmental Observers" to develop comprehensive, community-scaled climate change health assessments.[42] During a recent drought on the Navajo Reservation, traditional knowledge and western approaches were also applied together, as researchers worked with Navajo elders to observe meteorological and hydrological changes and other phenomena in an effort to assess and reduce disaster risks.[43]

Key Message 1: Forests, Fires, and Food

Observed and future impacts from climate change threaten Native Peoples' access to traditional foods such as fish, game, and wild and cultivated crops, which have provided sustenance as well as cultural, economic, medicinal, and community health for generations.

Climate change impacts on forests and ecosystems are expected to have direct effects on culturally important plant and animal species, which will affect tribal sovereignty, culture, and economies.[2,4] Warmer temperatures and more frequent drought are expected to cause dieback and tree loss of several tree and plant species (such as birch, brown ash, and sweet grass) important for Native artistic, cultural, and economic purposes, including tourism.[22] Tribal access to valued resources is threatened by climate change impacts causing habitat degradation, forest conversion, and extreme changes in ecosystem processes.[44]

Observed impacts from both the causes and consequences of climate change, and added stressors such as extractive industry practices on or near Native lands, include species loss and shifts in species range.[1,45,46,47] There have also been observed changes in the distribution and population density of wildlife species, contraction or expansion of some plant species' range, and the northward migration of some temperate forest species.[4,48] For example, moose populations in Maine and similar locations are expected to decline because of loss of preferred habitat and increased winter temperatures, which are enabling ticks to survive through the winter and causing damage from significant infestation of the moose.[22]


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Harvesting traditional foods is important to Native Peoples' culture, health, and economic well being. In the Great Lakes region, wild rice is unable to grow in its traditional range due to warming winters and changing water levels.

Loss of biodiversity, changes in ranges and abundance of culturally important native plants and animals, increases in invasive species, bark beetle damage to forests, and increased risk of forest fires have been observed in the Southwest, across much of the West, and in Alaska (see also Appendix 3: Climate Science Supplement, Figure 31; Ch. 7: Forests; Ch. 8: Ecosystems).[4,30,48,49] Changes in ocean temperature and acidity affect distribution and abundance of important food sources, like fish and shellfish (Ch. 2: Our Changing Climate; Ch. 24: Oceans).

Rising temperatures and hotter, drier summers are projected to increase the frequency and intensity of large wildfires (see Ch. 7: Forests).[44] Warmer, drier, and longer fire seasons and increased forest fuel load will lead to insect outbreaks and the spread of invasive species, dry grasses, and other fuel sources (see Ch. 7: Forests). Wildfire threatens Native and tribal homes, safety, economies, culturally important species, medicinal plants, traditional foods, and cultural sites. *"Fire affects the plants, which affect the water, which affects the fish, which affect terrestrial plants and animals, all of which the Karuk rely on for cultural perpetuity."*[50]

In interior Alaska, rural Native communities are experiencing new risks associated with climate change related wildfires in boreal forests and Arctic tundra (see also Ch. 22: Alaska).[1,51] Reliance on local, wild foods and the isolated nature of these communities, coupled with their varied preparedness and limited ability to deal with wildfires, leaves many communities at an increased risk of devastation brought on by fires. While efforts are being made to better coordinate rural responses to wildfires in Alaska, current responses are limited by organization and geographic isolation.[48]

Indigenous peoples have historically depended on the gathering and preparation of a wide variety of local plant and animal species for food (frequently referred to as traditional foods), medicines, ceremonies, community cohesion, and economic health for countless generations.[2,52] These include corn, beans, squash, seals, fish, shellfish, bison, bear, caribou, walrus, moose, deer, wild rice, cottonwood trees, and a multitude of native flora and fauna.[2,45,47,49,52,53,54,55,56,57] A changing climate affects the availability, tribal access to, and health of these resources.[1,2,4,47,57,58,59,60] This in turn threatens tribal customs, cultures, and identity.

Medicinal and food plants are becoming increasingly difficult to find or are no longer found in historical ranges.[2,56] For example, climate change and other environmental stressors are affecting the range, quality, and quantity of berry resources for the Wabanaki tribes in the Northeast.[2,61] The Karuk people in California have experienced a near elimination of both salmonids and acorns, which comprise 50% of a traditional Karuk diet.[62] In the Great Lakes region, wild rice is unable to grow in its traditional range due to warming winters and changing water levels, affecting the Anishinaabe peoples' culture, health, and well-being.[54]

Subsequent shifts from traditional lifestyles and diet, compounded by persistent poverty, food insecurity, the cost of non-traditional foods, and poor housing conditions have led to increasing health problems in communities, also increasing the risk to food and resource security.[1,2,16] Climate change is likely to amplify other indirect effects to traditional foods and resources, including limited access to gathering places and hunting grounds and environmental pollution.[4,57,59]

Human-caused stresses such as dam building have greatly reduced salmon on the Klamath River.

Key Message 2: Water Quality and Quantity

A significant decrease in water quality and quantity due to a variety of factors, including climate change, is affecting drinking water, food, and cultures. Native communities' vulnerabilities and limited capacity to adapt to water-related challenges are exacerbated by historical and contemporary government policies and poor socioeconomic conditions.

Native communities and tribes in different parts of the U.S. have observed changes in precipitation affecting their water resources. On the Colorado Plateau, tribes have been experiencing drought for more than a decade.[63,64] Navajo elders have observed long-term decreases in annual snowfall over the past century, a transition from wet to dry conditions in the 1940s, and a decline in surface water features.[20] Changes in long-term average temperature and precipitation have produced changes in the physical and hydrologic environment, making the Navajo Nation more susceptible to drought impacts, and some springs and shallow water wells on the Navajo Nation have gone dry.[43] Southwest tribes have observed damage to their agriculture and livestock, the loss of springs and medicinal and culturally important plants and animals, and impacts on drinking water supplies.[63,64,65,66] In the Northwest, tribal treaty rights to traditional territories and resources are being affected by the reduction of rainfall and snowmelt in the mountains, melting glaciers, rising temperatures, and shifts in ocean currents.[52,58,67] In Hawaiʻi, Native peoples have observed a shortening of the rainy season, increasing intensity of storms and flooding, and a rainfall pattern that has become unpredictable.[38] In Alaska, water availability, quality, and quantity are threatened by the consequences of permafrost thaw, which has damaged community water infrastructure, as well as by the northward extension of diseases such as those caused by the *Giardia* parasite, a result of disease-carriers like beavers moving northward in response to rising temperatures.[68] The impact of historical federal policies, such as the late 1800s allotment policy and practices regarding Native access to treaty-protected resources,[69] reverberate in current practices, such as states and the government permitting oil drilling and hydraulic fracturing on lands in and around reservations but outside of tribal jurisdiction (for example, a 2013 pipeline spill upstream of tribal reservations in Western North Dakota, and others). Such policies and practices exacerbate the threat to water quality and quantity for Native communities.

Coal plant and fishermen, Navajo Reservation

Native American tribes have unique and significant adaptation needs related to climate impacts on water.[66] There is little available data to establish baseline climatic conditions on tribal lands, and many tribes do not have sufficient capacity to monitor changing conditions.[63] Without scientific monitoring, tribal decision-makers lack the data needed to quantify and evaluate current conditions and emerging trends in precipitation, streamflow, and soil moisture, and to plan and manage resources accordingly.[10,64,66] However, some existing efforts to document climate impacts on water resources could be replicated in other regions to assess hydrologic vulnerabilities.[58]

Water infrastructure is in disrepair or lacking on some reservations.[43,70] Approximately 30% of people on the Navajo Nation are not served by municipal systems and must haul water to meet their daily needs.[19,43] Longer-term impacts of this lack of control over water access are projected to include loss of traditional agricultural crops.[19,43] Furthermore, there is an overall lack of financial resources to support basic water infrastructure on tribal lands.[63] Uncertainty associated with undefined tribal water rights make it difficult to determine strategies to deal with water resource issues.[70] Potential impacts to treaty rights and water resources exist, such as a reduction of groundwater and drinking water availability and water quality decline, including impacts from oil and natural gas extraction and sea level rise-induced saltwater intrusion into coastal freshwater aquifers (see also Ch. 3: Water).[7] New datasets on climate impacts on water in many locations throughout Indian Country, such as the need to quantify available water and aquifer monitoring, will be important for improved adaptive planning.

Sand Dune Expansion

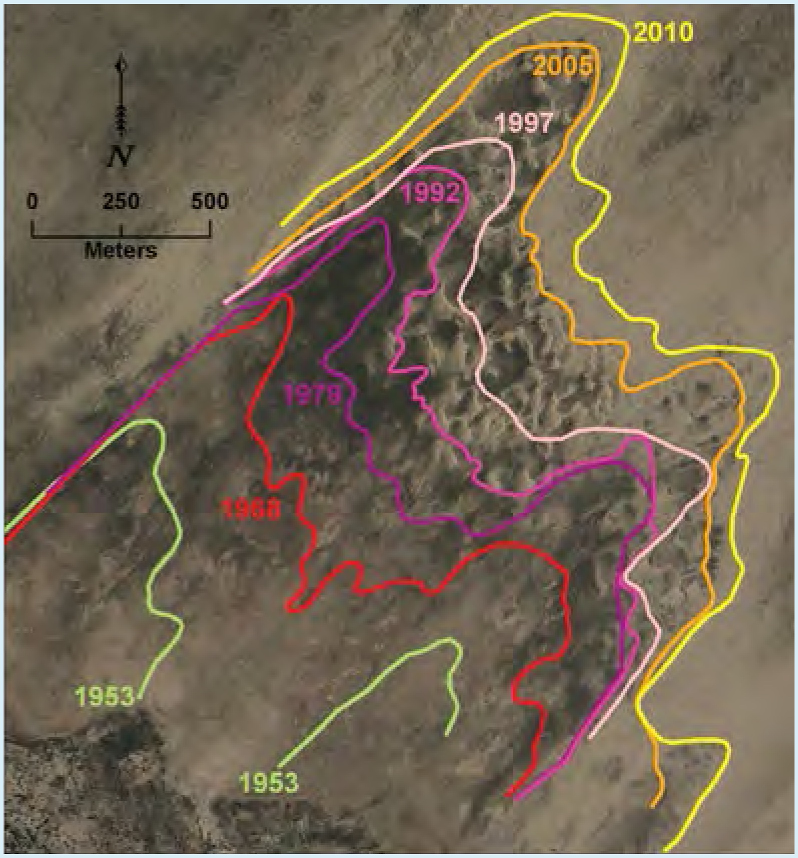

Figure 12.3. On the Arizona portion of the Navajo Nation, recurring drought and rising temperatures have accelerated growth and movement of sand dunes. Map above shows range and movement of Great Falls Dune Field from 1953 to 2010. Moving and/or growing dunes can threaten roads, homes, traditional grazing areas, and other tribal assets. (Figure source: Redsteer et al. 2011[55]).

Key Message 3: Declining Sea Ice

Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and loss to settlements, food insecurity, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.

> *"…since the late 1970s, communities along the coast of the northern Bering and Chukchi Seas have noticed substantial changes in the ocean and the animals that live there. While we are used to changes from year-to-year in weather, hunting conditions, ice patterns, and animal populations, the past two decades have seen clear trends in many environmental factors. If these trends continue, we can expect major, perhaps irreversible, impacts to our communities…."*
>
> – C. Pungowiyi, personal communication[71]

Scientists across the Arctic have documented rising regional temperatures over the past few decades at twice the global rate, and indigenous Arctic communities have observed these changes in their daily lives.[1] This temperature increase – which is expected to continue with future climate change – is accompanied by significant reductions in sea ice thickness and extent, increased permafrost thaw, more extreme weather and severe storms, and changes in seasonal ice melt/freeze of lakes and rivers, water temperature, sea level rise, flooding patterns, erosion, and snowfall timing and type (see also Ch. 2:

Sea Ice Cover Reaches Record Low

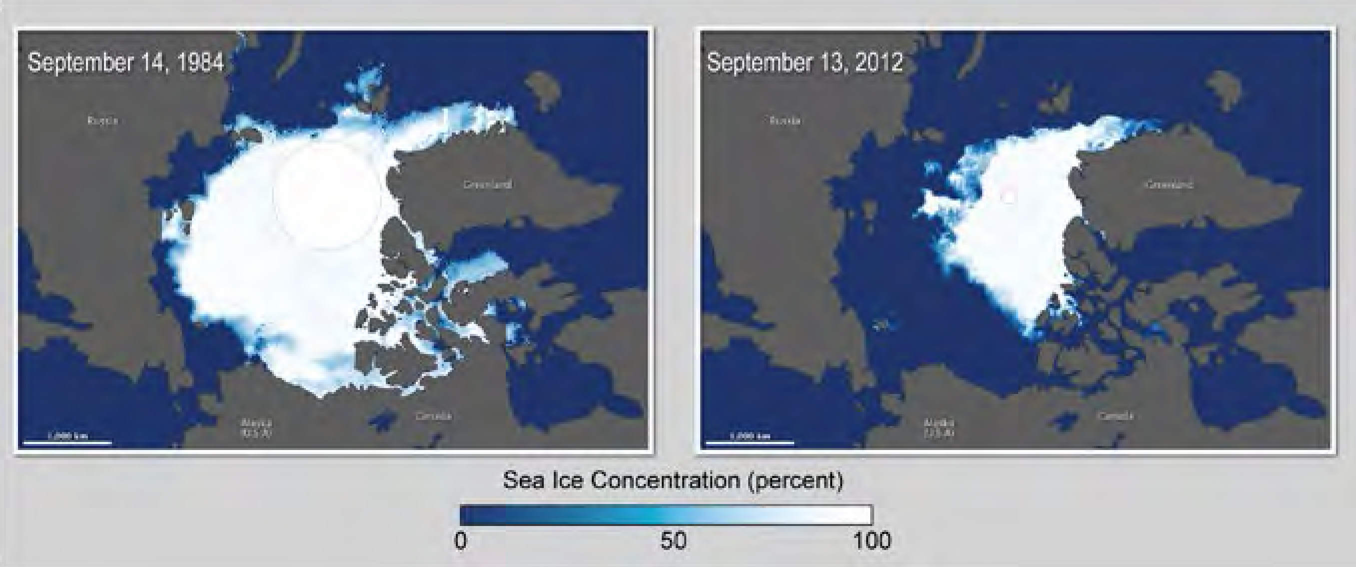

Figure 12.4. In August and September 2012, sea ice covered less of the Arctic Ocean than any time since the beginning of reliable satellite measurements (1979). The long-term retreat of sea ice has occurred faster than climate models had predicted. The average minimum extent of sea ice for 1979-2000 was 2.59 million square miles. The image on the left shows Arctic minimum sea ice extent in 1984, which was about the average minimum extent for 1979-2000. The image on the right shows that the extent of sea ice had dropped to 1.32 million square miles at the end of summer 2012. Alaska Native coastal communities rely on sea ice for many reasons, including its role as a buffer against coastal erosion from storms. (Figure source: NASA Earth Observatory 2012[77]).

Our Changing Climate).[71,72,73,74,75] These climate-driven changes in turn increase the number of serious problems for Alaska Native populations, which include injury from extreme or unpredictable weather and thinning sea ice, which can trap people far from home; changing snow and ice conditions that limit safe hunting, fishing, or herding practices; malnutrition and food insecurity from lack of access to subsistence food; contamination of food and water; increasing economic, mental, and social problems from loss of culture and traditional livelihood; increases in infectious diseases; and the loss of buildings and infrastructure from permafrost erosion and thawing, resulting in the relocation of entire communities (Ch. 22: Alaska).[1,68,71,75,76]

Alaska Native Inupiat and Yup'ik experts and scientists have observed stronger winds than in previous decades,[71,75,78] observations

Arctic Marine Food Web

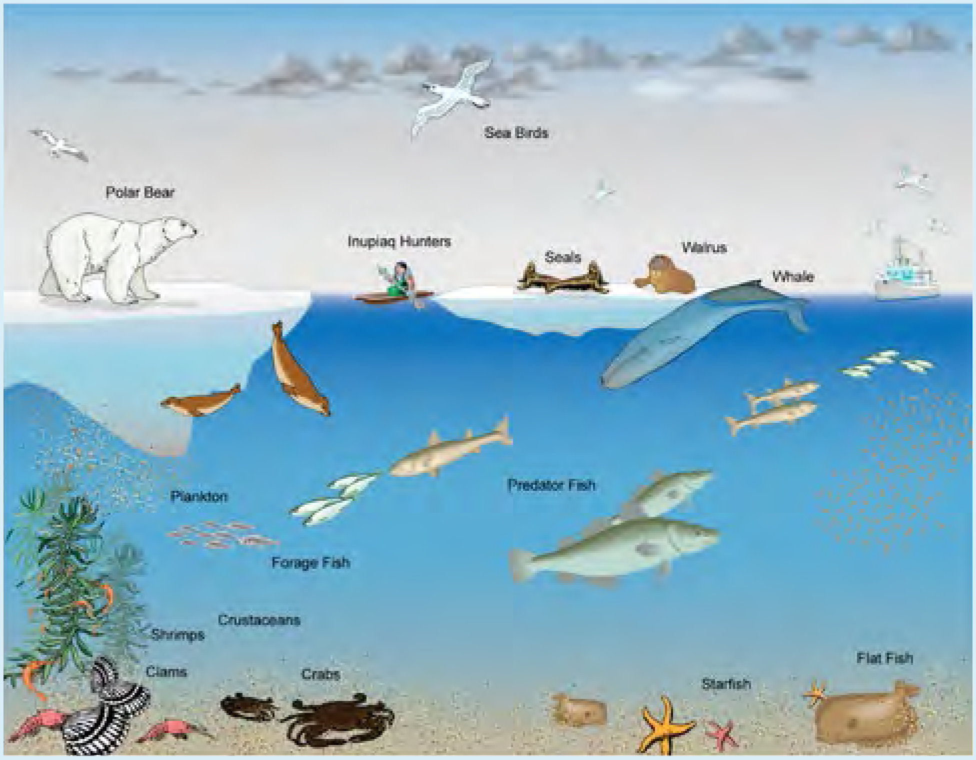

Figure 12.5. Dramatic reductions in Arctic sea ice and changes in its timing and composition affect the entire food web, including many Inupiaq communities that continue to rely heavily on subsistence hunting and fishing. (Figure source: NOAA NCDC).

that are consistent with scientific findings showing changing Arctic wind patterns, which in turn influence loss of sea ice and shifts in North American and European weather.[79] They also observe accelerated melting of ice and snow, and movement of ice and marine mammals far beyond accessible range for Native hunters.[1] Thinning sea ice, earlier ice break-up, increasing temperatures, and changes in precipitation (for example, in the timing and amount of snow) also cause changes in critical feeding, resting, breeding, and denning habitats for arctic mammals important as subsistence foods, like polar bears, walrus, and seals.[1,73,75,80]

Key Message 4: Permafrost Thaw

Alaska Native communities are increasingly exposed to health and livelihood hazards from increasing temperatures and thawing permafrost, which are damaging critical infrastructure, adding to other stressors on traditional lifestyles.

The increased thawing of permafrost (permanently frozen soil) along the coasts and rivers is an especially potent threat to Alaska Native villages because it causes serious erosion, flooding, and destruction of homes, buildings, and roads from differential settlement, slumping, and/or collapse of underlying base sediments (see Ch. 2: Our Changing Climate; Ch.22: Alaska, Key Message 3).[81] This loss of infrastructure is further exacerbated by loss of land-fast sea ice, sea level rise, and severe storms.[1,82,83] At this time, more than 30 Native villages in Alaska (such as Newtok and Shishmaref) are either in need of, or in the process of, relocating their entire village.[1,84]

Serious public health issues arise due to damaged infrastructure caused by these multiple erosion threats. Among them are loss of clean water for drinking and hygiene, saltwater intrusion, and sewage contamination that could cause respiratory and gastrointestinal infections, pneumonia, and skin infections.[1,76,82,85] In addition, permafrost thaw is causing food insecurity in Alaska Native communities due to the thawing of ice cellars or ice houses used for subsistence food storage. This in turn leads to food contamination and sickness as well as dependence upon expensive, less healthy, non-traditional “store-bought” foods.[1,85,86]

Thawing Permafrost in Alaska

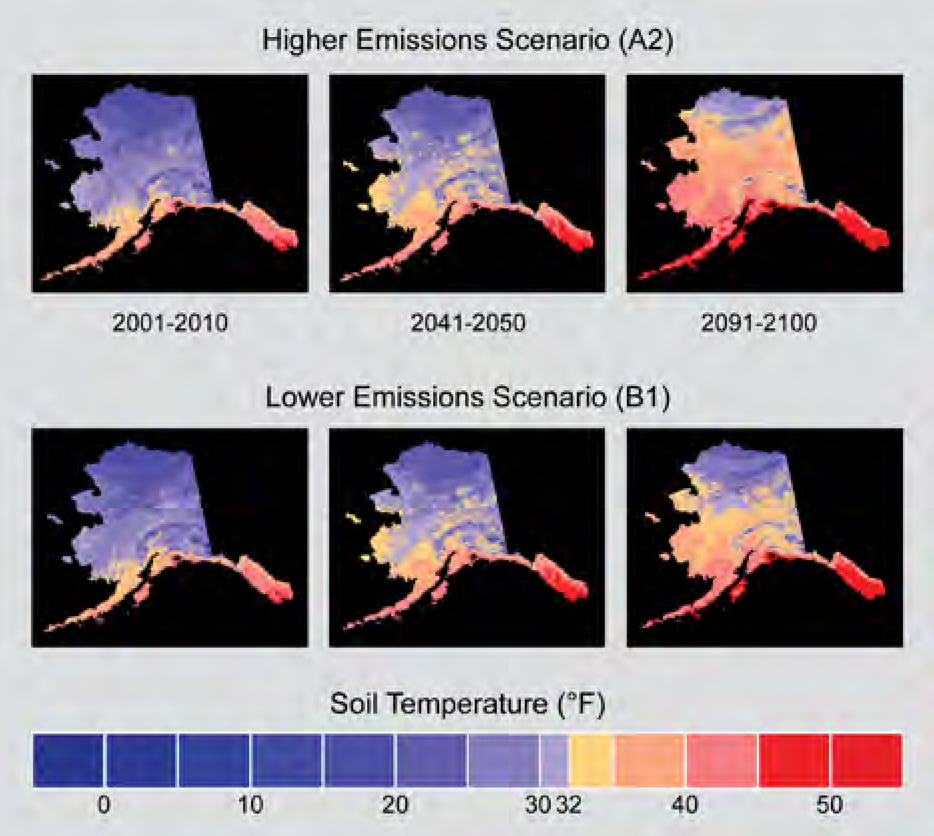

Figure 12.6. The maps show projected ground temperature at a depth of 3.3 feet assuming continued increases in emissions (A2 scenario) and assuming a substantial reduction in emissions (B1 scenario). Blue shades represent areas below freezing at a depth of 3.3 feet and yellow and red shades represent areas above freezing at that depth (see Ch. 22: Alaska for more details). Many Alaska Natives depend on permafrost for ice cellars to store frozen food, and replacing these cellars with electricity-driven freezers is expensive or otherwise infeasible. Permafrost thawing also affects infrastructure like roads and utility lines. (Figure source: Permafrost Lab, Geophysical Institute, University of Alaska Fairbanks).

Key Message 5: Relocation

Climate change related impacts are forcing relocation of tribal and indigenous communities, especially in coastal locations. These relocations, and the lack of governance mechanisms or funding to support them, are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.

Native peoples are no strangers to relocation and its consequences on their communities. Many eastern and southeastern tribal communities were forced to relocate to Canada or the western Great Lakes in the late 1700s and early 1800s and, later, to Oklahoma, compelling them to adjust and adapt to new and unfamiliar landscapes, subsistence resources, and climatic conditions. Forced relocations have continued into more recent times as well.[87] Now, many Native peoples in Alaska and other parts of the coastal United States, such as the Southeast and Pacific Northwest, are facing relocation as a consequence of climate change and additional stressors, such as food insecurity and unsustainable development and extractive practices on or near Native lands; such forms of displacement are leading to severe livelihood, health, and socio-cultural impacts on the communities.[1,3,23,38,45,88,89,90,91]

For example, Newtok, a traditional Yup'ik village in Alaska, is experiencing accelerated rates of erosion caused by the combination of decreased Arctic sea ice, thawing permafrost, and extreme weather events (Ch. 22: Alaska).[1,3] As a result, the community has lost critical basic necessities and infrastructure. While progress has been made toward relocation, limitations of existing federal and state statutes and regulations have impeded their efforts, and the absence of legal authority and a governance structure to facilitate relocation are significant barriers to the relocation of Newtok and other Alaska Native villages.[3,88,92] Tribal communities in coastal Louisiana are experiencing climate change induced rising sea levels, along with saltwater intrusion, subsidence, and intense erosion and land loss due to oil and gas extraction, levees, dams, and other river management techniques, forcing them to either relocate or try to find ways to save their land.[3,45] Tribal communities in Florida are facing potential displacement due to the risk of rising sea levels and saltwater intrusion inundating their reservation lands.[93] The Quileute tribe in northern Washington is responding to increased winter storms and flooding connected with increased precipitation by relocating some of their village homes and buildings to higher ground within 772 acres of Olympic National Park that has been transferred to them; the Hoh tribe is also looking at similar options for relocation.[90,94,95] Native Pacific Island communities, including those in Hawai'i and the U.S. affiliated Pacific Islands, are also being forced to consider relocation plans due to increasing sea level rise and storm surges.[38,96] While many Native communities are not necessarily being forced to relocate, they are experiencing other social and cultural forms of displacement. For example, rising sea levels are expected to damage Native coastal middens (sites reflecting past human activity such as food preparation) as well as Wabanaki coastal petroglyphs, leading to loss of culture and connection to their past for Northeast tribes.[22]


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Rising temperatures are causing damage in Native villages in Alaska as sea ice declines and permafrost thaws. Resident of Selawik, Alaska, and his granddaughter survey a water line sinking into the thawing permafrost, August 2011.

Currently, the U.S. lacks an institutional framework to relocate entire communities. National, state, local, and tribal government agencies lack the legal authority and the technical, organizational, and financial capacity to implement relocation processes for communities forcibly displaced by climate change.[3,12] New governance institutions, frameworks, and funding mechanisms are needed to specifically respond to the increasing necessity for climate change induced relocation.[3,88] To be effective and culturally appropriate, it is important that such institutional frameworks recognize the sovereignty of tribal governments and that any institutional development stems from significant engagement with tribal representatives.[12]

"In Indigenous cultures, it is understood that ecosystems are chaotic, complex, organic, in a constant state of flux, and filled with diversity. No one part of an ecosystem is considered more important than another part and all parts have synergistic roles to play. Indigenous communities say that 'all things are connected' – the land to the air and water, the earth to the sky, the plants to the animals, the people to the spirit."

– Patricia Cochran, Inupiat Leader[97]

12: INDIGENOUS PEOPLES, LANDS, AND RESOURCES

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

A central component of the assessment process was participation by members of the Chapter Author Team in a number of climate change meetings attended by indigenous peoples and other interested parties, focusing on issues relevant to tribal and indigenous peoples. These meetings included:

Oklahoma Inter-Tribal Meeting on Climate Variability and Change held on December 12, 2011, at the National Weather Center, Norman, OK, attended by 73 people.[56]

Indigenous Knowledge and Education (IKE) Hui Climate Change and Indigenous Cultures forum held in January 2012 in Hawai'i and attended by 36 people.[38]

Alaska Forum on the Environment held from February 6-10, 2012, at the Dena'ina Convention Center in Anchorage, Alaska, and attended by about 1400 people with approximately 30 to 60 people per session.[27]

Stories of Change: Coastal Louisiana Tribal Communities' Experiences of a Transforming Environment, a workshop held from January 22-27, 2012, in Pointe-au-Chien, Louisiana, and attended by 47 people.[45]

American Indian Alaska Native Climate Change Working Group 2012 Spring Meeting held from April 23–24, 2012, at the Desert Diamond Hotel-Casino in Tucson, Arizona, and attended by 80 people.[98]

First Stewards Symposium. First Stewards: Coastal Peoples Address Climate Change. National Museum of the American Indian, Washington DC. July 17-20, 2012.[30]

In developing key messages, the Chapter Author Team engaged in multiple technical discussions via teleconferences from August 2011 to March 2012 as they reviewed more than 200 technical inputs provided by the public, as well as other published literature and professional judgment. Subsequently, the Chapter Author Team teleconferenced weekly between March and July 2012 for expert deliberations of draft key messages by the authors. Each key message was defended by the entire author team before being selected for inclusion in the chapter report. These discussions were supported by targeted consultation with additional experts by the lead author of each message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Observed and future impacts from climate change threaten Native Peoples' access to traditional foods such as fish, game, and wild and cultivated crops, which have provided sustenance as well as cultural, economic, medicinal, and community health for generations.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe loss of biodiversity, impacts on culturally important native plants and animals, increases in invasive species, bark beetle damage to forests, and increased risk of forest fires that have been observed across the United States.[4,7,22,49,52,58]

Climate drivers associated with this key message are also discussed in Ch. 2: Our Changing Climate.

There are also many relevant and recent peer-reviewed publications[1,2,4,48,52,58,66] describing the northward migration of the boreal forest and changes in the distribution and density of wildlife species that have been observed.

Observed impacts on plant and animal species important to traditional foods, ceremonies, medicinal, cultural and economic well-being, including species loss and shifts in species range, are well-documented.[1,2,4,6,7,22,45,46,47,52]

New information and remaining uncertainties

A key uncertainty is how indigenous people will adapt to climate change, given their reliance on local, wild foods and the isolated nature of some communities, coupled with their varied preparedness and limited ability to deal with wildfires. Increased wildfire occurrences may affect tribal homes, safety, economy, culturally important species, medicinal plants, traditional foods, and cultural sites.

There is uncertainty as to the extent that climate change will affect Native American and Alaska Natives' access to traditional foods such as salmon, shellfish, crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, confidence is **very high** that observed and future impacts from climate change, such as increased frequency and intensity of wildfires, higher temperatures, changes in sea ice, and ecosystem changes, such as forest loss and habitat damage, are threatening Native American and Alaska Natives' access to traditional foods such as salmon, shellfish, crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

A significant decrease in water quality and quantity due to a variety of factors, including climate change, is affecting drinking water, food, and cultures. Native communities' vulnerabilities and limited capacity to adapt to water-related challenges are exacerbated by historical and contemporary government policies and poor socioeconomic conditions.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

There are numerous examples of tribal observations of changes in precipitation, rainfall patterns, and storm intensity and impacts on surface water features, agriculture, grazing, medicinal and culturally important plants and animals, and water resources.[2,4,6,7,43,52,55,58,63,64,65,66]

Examples of ceremonies are included in the Oklahoma Inter-Tribal Meeting on Climate Variability and Change Meeting Summary Report.[56] Water is used for some ceremonies, so it can be problematic when there is not enough at the tribe's disposal.[52,56,66] More than one tribe at the meeting also expressed how heat has been a problem during ceremonies because the older citizens cannot go into lodges that lack air conditioning.[56]

New information and remaining uncertainties

There is limited data to establish baseline climatic conditions on tribal lands, and many tribes do not have sufficient capacity to monitor changing conditions.[10,52,63,66] Without monitoring, tribal decision-makers lack the data needed to quantify and evaluate the current conditions and emerging trends in precipitation, streamflow, and soil moisture, and to plan and manage resources accordingly.[10,52,64,66]

Water infrastructure is in disrepair or lacking on some reservations.[43,70] There is an overall lack of financial resources to support basic water infrastructure on tribal lands, such as is found in the Southwest.[63]

Tribes that rely on water resources to maintain their cultures, religions, and life ways are especially vulnerable to climate change. Monitoring data is needed to establish baseline climatic conditions and to monitor changing conditions on tribal lands. Uncertainty associated with undefined tribal water rights makes it difficult to determine strategies to deal with water resource issues.[70]

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, confidence is **very high** that decreases in water quality and quantity are affecting Native Americans and Alaska Natives' drinking water supplies, food, cultures, ceremonies, and traditional ways of life. Based upon extensive evidence, there is **very high** confidence that Native communities' vulnerabilities and lack of capacity to adapt to climate change are exacerbated by historical and contemporary federal and state land-use policies and practices, political marginalization, legal issues associated with tribal water rights, water infrastructure deficiencies, and poor socioeconomic conditions.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and loss to settlements, food insecurity, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that summer sea ice is rapidly declining is based on satellite data and other observational data and is incontrovertible. The seasonal pattern of observed loss of Arctic sea ice is generally consistent with simulations by global climate models, in which the extent of sea ice decreases more rapidly in summer than in winter (Ch. 2: Our Changing Climate). Projections by these models indicate that the Arctic Ocean is projected to become virtually ice-free in summer before mid-century, and models that best match historical trends project a nearly sea ice-free Arctic in summer by the 2030s.[74] Extrapolation of the present observed trends suggests an even earlier ice-free Arctic in summer. (Ch. 2: Our Changing Climate and Ch. 22: Alaska).

Sea ice loss is altering marine ecosystems; allowing for greater ship access and new development; increasing Native community vulnerabilities due to changes in sea ice thickness and extent; destroying housing, village sanitation and other infrastructure (including entire villages); and increasing food insecurity due to lack of access to subsistence food and loss of cultural traditions. Evidence for all these impacts of sea ice loss is well-documented in field studies, indigenous knowledge, and scientific literature.[1,2,3,71,73,75,78]

New information and remaining uncertainties

A key uncertainty is how indigenous peoples will be able to maintain historical subsistence ways of life, which include hunting, fishing, harvesting, and sharing, and sustain the traditional relationship with the environment given the impacts from sea ice decline and changes. Increased sea ice changes and declines are already causing increasingly hazardous hunting and traveling conditions along ice edges; damage to homes and infrastructure from erosion; changes in habitat for subsistence foods and species, with overall impacts on food insecurity and for species necessary for medicines, ceremonies, and other traditions.[1] The effects of sea ice loss are exacerbated by other climate change driven impacts such as changes in snow and ice, weather, in-migration of people, poverty, lack of resources to respond to changes, and contamination of subsistence foods.[1,2]

Additional observations and monitoring are needed to more adequately document ice and weather changes.

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, there is **very high** confidence that loss of sea ice is affecting the traditional life ways of Native communities in a number of important ways, such as more hazardous travel and hunting conditions along the ice edge; erosion damage to homes, infrastructure, and sanitation facilities (including loss of entire villages); changes in ecosystem habitats and, therefore, impacts on food security; and socioeconomic and health impacts from cultural and homeland losses.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Alaska Native communities are increasingly exposed to health and livelihood hazards from increasing temperatures and thawing permafrost, which are damaging critical infrastructure, adding to other stressors on traditional lifestyles.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Given the evidence base and uncertainties, confidence is high that rising temperatures are thawing permafrost and that this thawing is expected to continue (Ch. 2: Our Changing Climate) Permafrost temperatures are increasing over Alaska and much of the Arctic. Regions of discontinuous permafrost (where annual average soil temperatures of already close to 32°F) are highly vulnerable to thaw (Ch. 2: Our Changing Climate).[81]

There are also many relevant and recent peer-reviewed publications[1,3,82,83] describing the impact of permafrost thaw on Alaska Native villages. Over 30 Native villages in Alaska are in need of relocation or are in the process of being moved. Recent work[1,84,85] documents public health issues such as contamination of clean water for drinking and hygiene and food insecurity through thawing of ice cellars for subsistence food storage.

New information and remaining uncertainties

Improved models and observational data (see Ch. 22: Alaska) confirmed many of the findings from the prior 2009 Alaska assessment chapter, which informed the 2009 National Climate Assessment.[99]

A key uncertainty is how indigenous peoples in Alaska will be able to sustain traditional subsistence life ways when their communities and settlements on the historical lands of their ancestors are collapsing due to permafrost thawing, flooding, and erosion combined with loss of shore-fast ice, sea level rise, and severe storms, especially along the coasts and rivers.[1]

Another uncertainty is how indigenous communities can protect the health and welfare of the villagers from permafrost-thaw-caused public health issues of drinking water contamination, loss of traditional food storage, and potential food contamination.[1]

It is uncertain how Native communities will be able to effectively relocate and maintain their culture, particularly because there are no institutional frameworks, legal authorities, or funding to implement relocation for communities forced to relocate.[1,3,12]

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, confidence is **very high** that Alaska Native communities are increasingly exposed to health and livelihood hazards from permafrost thawing and increasing temperatures, which are causing damage to roads, water supply and sanitation systems, homes, schools, ice cellars, and ice roads, and threatening traditional lifestyles.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Climate change related impacts are forcing relocation of tribal and indigenous communities, especially in coastal locations. These relocations, and the lack of governance mechanisms or funding to support them, are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

There is well-documented evidence that tribal communities are vulnerable to coastal erosion that could force them to relocate.[1,3,23,38,88,89] For example, tribal communities in Alaska, such as Newtok, Kivalina, and Shishmaref, are experiencing accelerated rates of erosion caused by the combination of decreased Arctic sea ice, thawing permafrost, and extreme weather events, resulting in loss of basic necessities and infrastructure (see also Ch. 22: Alaska).[1,3,88,91]

Tribal communities in coastal Louisiana are experiencing climate-induced rising sea levels, along with saltwater intrusion and intense erosion and land loss due to oil and gas extraction and river management, forcing them to either relocate or try to find ways to save their land (see also Ch. 25: Coasts and Ch. 17 Southeast).[3,45] Tribal communities in Florida are facing potential displacement due to the risk of rising sea levels and saltwater intrusion inundating their reservation lands.[93] The Quileute tribe in northern Washington is relocating some of their village homes and buildings to Olympic National Park in response to increased winter storms and flooding connected with increased precipitation; the Hoh tribe is also considering similar options.[90,94]

Native Pacific Island communities are being forced to consider relocation plans due to increasing sea level rise and storm surges (see also Ch. 23: Hawai‘i and Pacific Islands).[38]

New information and remaining uncertainties

A key uncertainty is the extent to which the combination of other impacts (for example, erosion caused by dredging for oil pipelines or second-order effects from adaptation-related development projects) will coincide with sea level rise and other climate-related issues to increase the rate at which communities will need to relocate.[1,3,38]

Another key uncertainty is how communities will be able to effectively relocate, maintain their communities and culture, and reduce the impoverishment risks that often go along with relocation.[1,3,38] The United States lacks an institutional framework to relocate entire communities, and national, state, local, and tribal government agencies lack the legal authority and the technical, organizational, and financial capacity to implement relocation processes for communities forcibly displaced by climate change.[3,12]

Assessment of confidence based on evidence

Based on the evidence, there is **very high** confidence that tribal communities in Alaska, coastal Louisiana, Pacific Islands, and other coastal locations are being forced to relocate due to sea level rise, coastal erosion, melting permafrost, and/or extreme weather events. There is **very high** confidence that these relocations and the lack of governance mechanisms or funding to support them are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.

Climate Change Impacts in the United States

CHAPTER 13
LAND USE AND LAND COVER CHANGE

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

13 LAND USE
AND LAND COVER CHANGE

Key Messages

1. **Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.**
2. **Land-use and land-cover changes affect local, regional, and global climate processes.**
3. **Individuals, businesses, non-profits, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.**
4. **Choices about land use and land management may provide a means of reducing atmospheric greenhouse gas levels.**

In addition to emissions of heat-trapping greenhouse gases from energy, industrial, agricultural, and other activities, humans also affect climate through changes in land *use* (activities taking place on land, like growing food, cutting trees, or building cities) and land *cover* (the physical characteristics of the land surface, including grain crops, trees, or concrete).[1] For example, cities are warmer than the surrounding countryside because the greater extent of paved areas in cities affects how water and energy are exchanged between the land and the atmosphere. This increases the exposure of urban populations to the effects of extreme heat events. Decisions about land use and land cover can therefore affect, positively or negatively, how much our climate will change and what kind of vulnerabilities humans and natural systems will face as a result.

The impacts of changes in land use and land cover cut across all regions and sectors of the National Climate Assessment. Chapters addressing each region discuss land-use and land-cover topics of particular concern to specific regions. Similarly, chapters addressing sectors examine specific land-use matters. In particular, land cover and land use are a major focus for sectors such as agriculture, forests, rural and urban communities, and Native American lands. By contrast, the key messages of this chapter are national in scope and synthesize the findings of other chapters regarding land cover and land use.


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Land-use and land-cover changes affect climate processes: Above, development along Colorado's Front Range.

Land uses and land covers change over time in response to evolving economic, social, and biophysical conditions.[2] Many of these changes are set in motion by individual landowners and land managers and can be quantified from satellite measurements, aerial photographs, on-the-ground observations, and reports from landowners and users.[3,4] Over the past few decades, the most prominent land changes within the U.S. have been changes in the amount and kind of forest cover due to logging practices and development in the Southeast and Northwest and to urban expansion in the Northeast and Southwest.

Because humans control land use and, to a large extent, land cover, individuals, businesses, non-profit organizations, and governments can make land decisions to adapt to and/or reduce the effects of climate change. Often the same land-use decision can serve both aims. Adaptation options (those aimed at coping with the effects of climate change) include varying the local mix of vegetation and concrete to reduce heat in cities or elevating homes to reduce exposure to sea level rise or flooding. Land-use and land-cover-related options for mitigating climate change (reducing the speed and amount of climate change) include expanding forests to accelerate removal of carbon from the atmosphere, modifying the way cities are built and organized to reduce energy and motorized transportation demands, and altering agricultural management practices to increase carbon storage in soil.

Despite this range of climate change response options, there are three main reasons why private and public landowners may choose not to modify land uses and land covers for climate adaptation or mitigation purposes. First, land decisions are influenced not only by climate but also by economic, cultural, legal, or other considerations. In many cases, climate-based land-change efforts to adapt to or reduce climate change meet with resistance because current practices are too costly to modify and/or too deeply entrenched in local societies and cultures. Second, certain land uses and land covers are simply difficult to modify, regardless of desire or intent. For instance, the number of homes constructed in floodplains or the amount of irrigated agriculture can be so deeply rooted that they are difficult to change, no matter how much those practices might impede our ability to respond to climate change. Finally, the benefits of land-use decisions made by individual landowners with specific adaptation or mitigation goals do not always accrue to those landowners or even to their communities. Therefore, without some institutional intervention (such as incentives or penalties), the motivations for such decisions can be weak.

Recent Trends

In terms of land area, the U.S. remains a predominantly rural country, especially as its population increasingly gravitates towards urban areas. In 1910, only 46% of the U.S. population lived in urban areas, but by 2010 that figure had climbed to more than 81%.[5] In 2006 (the most recent year for which these data are available), more than 80% of the land cover in the lower 48 states was dominated by shrub/scrub vegetation, grasslands, forests, and agriculture.[6,7] Forests and grasslands, which include acreage used for timber production and grazing, account for more than half of all U.S. land use by area (Table 13.1), about 63% of which is in private ownership, though their distribution and ownership patterns vary regionally.[4] Agricultural land uses are carried out on 18% of U.S. surface area. Developed or built-up areas covered only about 5% of the country's land surface, with the greatest concentrations of urban areas in the Northeast, Midwest, and Southeast. This apparently small percentage of developed area belies its rapid expansion and does not include development that is dispersed in a mosaic among other land uses (like agriculture and forests). In particular, low-density housing developments (suburban and exurban areas), which are not well-represented in commonly used satellite measurements, have rapidly expanded throughout the U.S. over the last 60 years or so.[8,9] Based on Census data, areas settled at suburban and exurban densities (1 house per 1 to 40 acres on average) cover more than 15 times the land area settled at urban densities (1 house per acre or less) and covered five times more land area in 2000 than in 1950.[8]

Despite these rapid changes in developed land covers, the vast size of the country means that total land-cover changes in the U.S. may appear deceptively modest. Since 1973, satellite data show that the overall rate of land-cover changes nationally has averaged about 0.33% per year. Yet this small rate of change has produced a large cumulative impact. Between 1973 and 2000, 8.6% of the area of the lower 48 states experienced land-cover change, an area roughly equivalent to the combined land area of California and Oregon.[1]

U.S. Land-Cover Composition in 2000

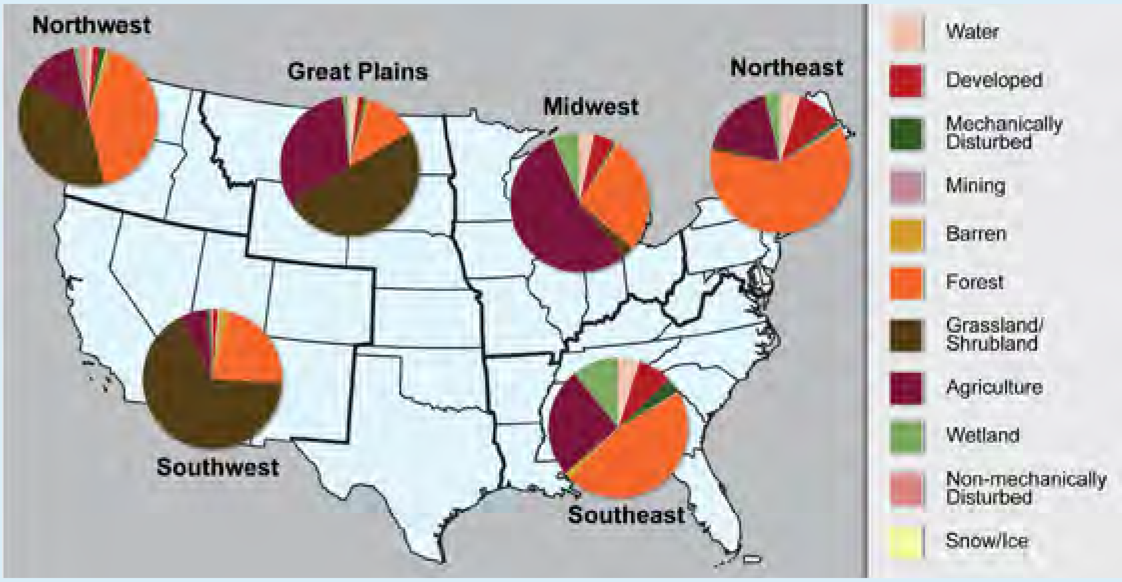

Figure 13.1. Map shows regional differences in land cover. These patterns affect climate and will be affected by climate change. They also influence the vulnerability and resilience of communities to the effects of climate change (Figure source: USGS Earth Resources Observation and Science (EROS) Center). (See Table 13.2 for definitions of mechanically and non-mechanically disturbed.)

These national-level annual rates of land changes mask considerable geographic variability in the types, rates, and causes of change.[3] Between 1973 and 2000, the Southeast region had the highest rate of change, due to active forest timber harvesting and replanting, while the Southwest region had the lowest rate of change.

Table 13.1. Circa-2001 land-cover statistics for the National Climate Assessment regions of the United States based on the National Land Cover Dataset,[7] and overall United States land-use statistics—circa 2007.[4]

Land Cover Class	Northeast	Southeast	Midwest	Great Plains	Southwest	Northwest	Alaska	Hawaii	United States	Land Use Class (ca 2007)	United States (ca 2007)
Agriculture	10.9%	23.0%	49.0%	29.7%	5.0%	10.0%	0.0%	4.0%	18.6%	Cropland	18.0%
Grassland, Shrub/Scrub, Moss, Lichen	3.4%	7.8%	2.9%	50.5%	65.7%	42.8%	44.9%	33.3%	39.2%	Grassland, Pasture, and Range	27.1%
Forest	52.4%	38.7%	23.7%	10.7%	19.9%	37.7%	22.4%	22.0%	23.2%[a]	Forest	29.7%[a]
Barren	0.8%	0.3%	0.2%	0.5%	3.7%	1.5%	7.7%	11.2%	2.6%	Special Use[b]	13.8%
Developed, Built-Up	9.6%	7.7%	8.0%	4.0%	2.7%	3.0%	0.1%	6.7%	4.0%	Urban	2.7%
Water, Ice, Snow	14.9%	7.3%	10.4%	1.9%	1.7%	3.2%	18.5%	21.7%	7.4%	Miscellaneous[c]	8.7%
Wetlands	8.0%	15.2%	5.8%	2.7%	0.7%	1.3%	6.4%	0.3%	5.0%		

[a] Definitional differences in the way certain categories are defined, such as the special uses distinction in the USDA Economic Research Service land use estimates, make direct comparisons between land use and land cover challenging. For example, forest land use (29.7%) exceeds forest cover (23.2%). Forest use definitions include lands where trees have been harvested and may be replanted, while forest cover is a measurement of the presence of trees.

[b] Special uses represent rural transportation, rural parks and wildlife, defense and industrial, plus miscellaneous farm and other special uses.

[c] Miscellaneous uses represent unclassified uses such as marshes, swamps, bare rock, deserts, tundra plus other uses not estimated, classified, or inventoried.

Table 13.2. Percentage change in land-cover type between 1973 and 2000 for the contiguous U.S. National Climate Assessment regions. These figures do not indicate the total amount of changes that have occurred, for example when increases in forest cover were offset by decreases in forest cover, and when cropland taken out of production was offset by other land being put into agricultural production. Data from USGS Land Cover Trends Project; Sleeter et al. 2013.[10]

Land Cover Type	Northeast	Southeast	Midwest	Great Plains	Southwest	Northwest
Grassland/Shrubland	0.73	0.31	0.59	1.55	-0.28	0.35
Forest	-2.02	-2.51	-0.93	-0.71	-0.49	2.39
Agriculture	-0.85	-1.62	-1.38	-1.60	-0.37	-0.35
Developed	1.36	2.28	1.34	0.43	0.51	0.51
Mining	0.14	-0.05	0.02	0.07	0.10	0.03
Barren	0.00	-0.01	0.00	0.00	0.00	0.00
Snow/Ice	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.03	0.45	0.08	0.23	0.03	-0.02
Wetland	-0.05	-0.69	-0.05	-0.13	-0.02	0.03
Mechanically Disturbed[a]	0.66	1.76	0.32	0.11	0.07	0.07
Non-mechanically Disturbed[b]	0.00	0.07	0.01	0.06	0.46	1.78

[a] Land in an altered and often un-vegetated state that, because of disturbances by mechanical means, is in transition from one cover type to another. Mechanical disturbances include forest clear-cutting, earthmoving, scraping, chaining, reservoir drawdown, and other similar human-induced changes.

[b] Land in an altered and often un-vegetated state that because of disturbances by non-mechanical means, is in transition from one cover type to another. Non-mechanical disturbances are caused by fire, wind, floods, animals, and other similar phenomena.

Projections

Future patterns of land use and land cover will interact with climate changes to affect human communities and ecosystems. At the same time, future climate changes will also affect how and where humans live and use land for various purposes.

National-scale analyses suggest that the general historical trends of land-use and land-cover changes (described above) will continue, with some important regional differences. These projections all assume continued population growth based on assumed or statistically modeled rates of birth, death, and migration,[11] which will result in changes in land use and land cover that are spread unevenly across the country. Urban land covers are projected to increase in the lower 48 states by 73% to 98% (to between 10% and 12% of land area versus less than 6% in 1997) by 2050, using low versus high growth assumptions, respectively. The slowest rate of increase is in the Northeast region, because of the high level of existing development and relatively low rates of population growth, and the highest rate is in the Northwest. In terms of area, the Northwest has the smallest projected increase in urban area (approximately 4.2 million acres) and the Southeast the largest (approximately 27.5 million acres).[12]

Changes in development density will have an impact on how population is distributed and affects land use and land cover. Some of the projected changes in developed areas will depend on assumptions about changes in household size and how concentrated urban development will be. Higher population density means less land is converted from forests or grasslands, but results in a greater extent of paved area. Projections based on estimates of housing-unit density allow the assessment of impacts of urban land-use growth by density class. Increases in low-density exurban areas will result in a greater area affected by development and are expected to increase commuting times and infrastructure costs.

The areas projected to experience exurban development will have less density of impervious surfaces (like asphalt or concrete). While about one-third of exurban areas are covered by impervious surfaces,[13] urban or suburban areas are about one-half concrete and asphalt. Impervious surfaces have a wide range of environmental impacts and thus represent a key means by which developed lands modify the movement of water, energy, and living things. For example, areas with more impervious surfaces like parking lots and roads tend to experience more rapid runoff, greater risk of flooding, and higher temperatures from the urban heat-island effect.

Projections of Settlement Densities (2010-2050)

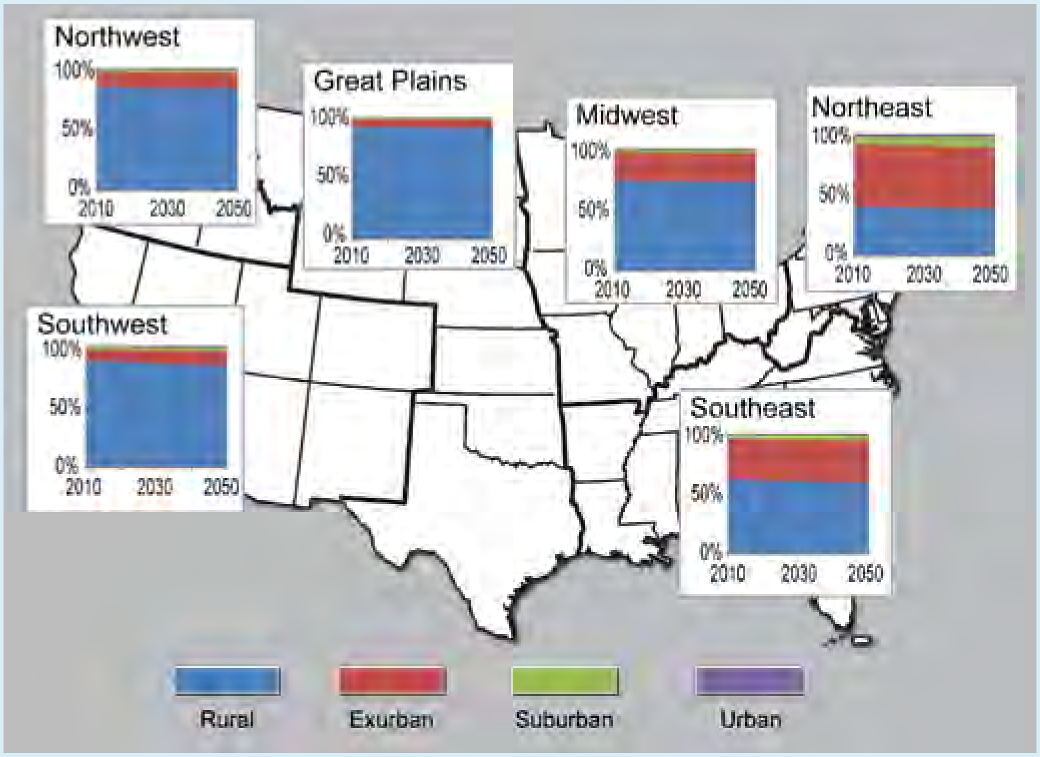

Figure 13.2. Projected percentages in each housing-unit density category for 2050 compared with 2010, assuming demographic and economic growth consistent with the high-growth emissions scenario (A2). (Data from U.S. EPA Integrated Climate and Land Use Scenarios).

Projections of both land-use and land-cover changes will depend to some degree on rates of population and economic growth. In general, scenarios that assume continued high growth produce more rapid increases in developed areas of all densities and in areas covered by impervious surfaces (paved areas and buildings) by 2050.[12,13]

Land-use scenarios project that exurban and suburban areas will expand nationally by 15% to 20% between 2000 and 2050,[13] based on high- and low-growth scenarios respectively. Land-cover projections by Wear[12] show that both cropland and forest are projected to decline most relative to 1997 (by 6% to 7%, respectively, by 2050) under a scenario of high population and economic growth and least (by 4% and 6%, respectively) under lower-growth scenarios. More forest than cropland is projected to be lost in the Northeast and Southeast, whereas more cropland than forest is projected to be lost in the Midwest and Great Plains.[14] Some of these regional differences are due to the current mix of land uses, others to the differential rates of urbanization in these different regions.

Projected Land Covers (2010-2050)

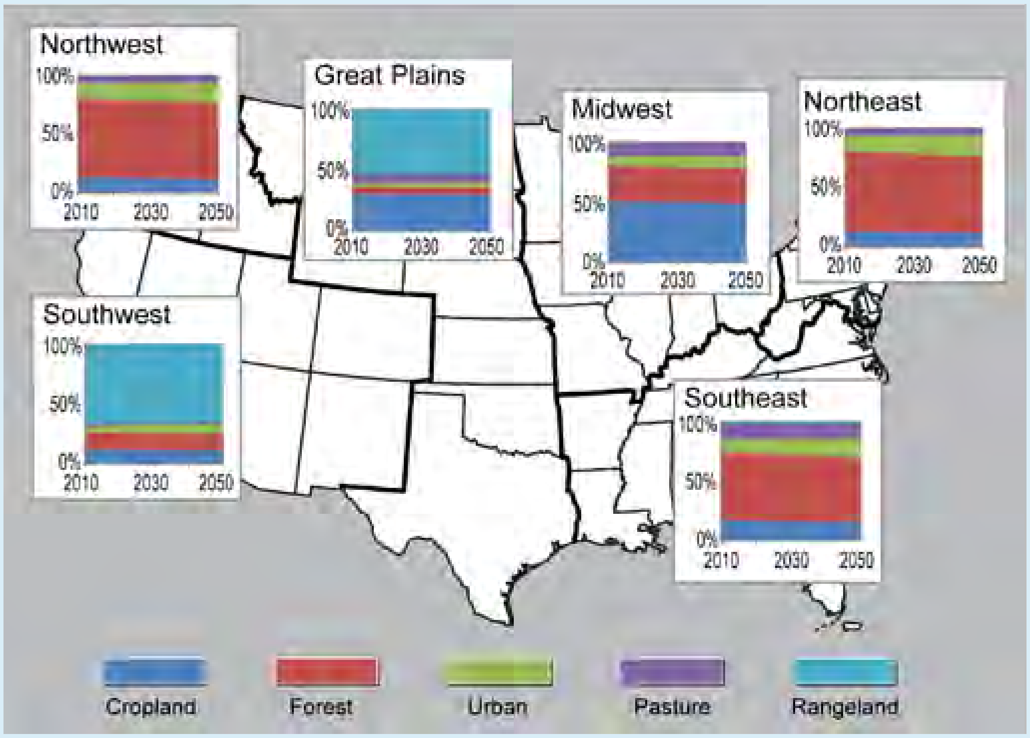

Figure 13.3. Projected percentages in each land-cover category for 2050 compared with 2010, assuming demographic and economic growth consistent with the high-growth emissions scenario (A2) (Data from USDA).

Key Message 1: Effects on Communities and Ecosystems

Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.

Decisions about land-use and land-cover change by individual landowners and land managers are influenced by demographic and economic trends and social preferences, which unfold at global, national, regional, and local scales. Policymakers can directly affect land use and land cover. For example, Congress can declare an area as federally protected wilderness, or local officials can set aside portions of a town for industrial development and create tax benefits for companies to build there. Climate factors typically play a secondary role in land decisions, if they are considered at all. Nonetheless, land-change decisions may affect the vulnerabilities of individuals, households, communities, businesses, non-profit organizations, and ecosystems to the effects of climate change.[15] A farmer's choice of crop rotation in response to price signals affects his or her farm income's susceptibility to drought, for example. Such choices, along with changes in climate can also affect the farm's demand for water for irrigation. Similarly, a developer's decision to build new homes in a floodplain may affect the new homeowners' vulnerabilities to flooding events. A decision to include culverts underneath a coastal roadway may facilitate migration of a salt marsh inland as sea level rises.

The combination of residential location choices with wildfire occurrence dramatically illustrates how the interactions between land use and climate processes can affect climate change impacts and vulnerabilities. Low-density (suburban and exurban) housing patterns in the U.S. have expanded and are projected to continue to expand.[13] One result is a rise in the amount of construction in forests and other wildlands[16] that in turn has increased the exposure of houses, other structures, and people to damages from wildfires, which are increasing. The number of buildings lost in the 25 most destructive fires in California history increased significantly in the 1990s and 2000s compared to the previous three decades.[17] These losses are one example of how changing development patterns can interact with a changing climate to create dramatic new risks. In the western United States, increasing frequencies of large wildfires and longer wildfire durations are strongly associated with increased spring and summer temperatures and an earlier

Building Loss by Fires at California Wildland-Urban Interfaces

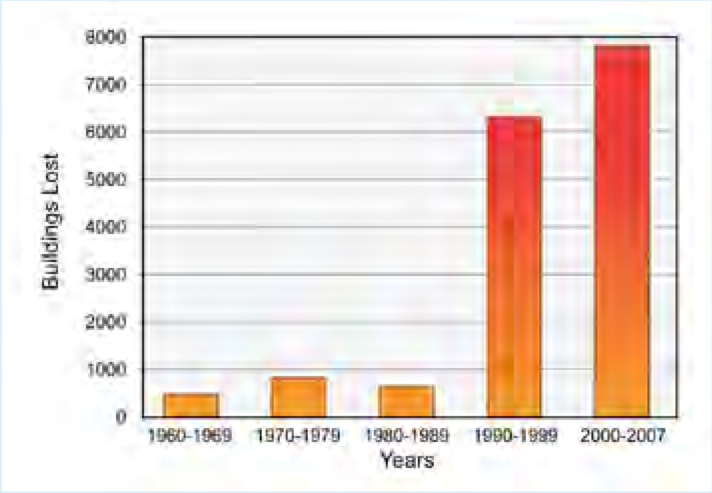

Figure 13.4. Many forested areas in the U.S. have experienced a recent building boom in what is known as the "wildland-urban interface." This figure shows the number of buildings lost from the 25 most destructive wildland-urban interface fires in California history from 1960 to 2007 (Figure source: Stephens et al. 2009[17]).

Construction near forests and wildlands is growing. Here, wildfire approaches a housing development.

spring snowmelt.[18] The effects on property loss of increases in the frequency and sizes of fires under climate change are also projected to increase in the coming decades because so many more people will have moved into increasingly fire-prone places (Ch. 2: Our Changing Climate; Ch. 7: Forests).

Key Message 2: Effects on Climate Processes

Land-use and land-cover changes affect local, regional, and global climate processes.

Land use and land cover play critical roles in the interaction between the land and the atmosphere, influencing climate at local, regional, and global scales.[19] There is growing evidence that land use, land cover, and land management affect the U.S. climate in several ways:

- Air temperature and near-surface moisture are changed in areas where natural vegetation is converted to agriculture.[20,21] This effect has been observed in the Great Plains and the Midwest, where overall dew point temperatures or the frequency of occurrences of extreme dew point temperatures have increased due to converting land to agricultural use.[21,22,23] This effect has also been observed where the fringes of California's Central Valley are being converted from natural vegetation to agriculture.[24] Other areas where uncultivated and conservation lands are being returned to cultivation, for example from restored grassland into biofuel production, have also experienced temperature shifts. Regional daily maximum temperatures were lowered due to forest clearing for agriculture in the Northeast and Midwest, and then increased in the Northeast following regrowth of forests due to abandonment of agriculture.[25]

- Conversion of rain-fed cropland to irrigated agriculture further intensifies the impacts of agricultural conversion on temperature. For example, irrigation in California has been found to reduce daily maximum temperatures by up to 9°F.[26] Model comparisons suggest that irrigation cools temperatures directly over croplands in California's Central Valley by 5°F to 13°F and increases relative humidity by 9% to 20%.[27] Observational data-based studies found similar impacts of irrigated agriculture in the Great Plains.[22,28]

- Both observational and modeling studies show that introduction of irrigated agriculture can alter regional precipitation.[29,30] It has been shown that irrigation in the Ogallala aquifer portion of the Great Plains can affect precipitation as far away as Indiana and western Kentucky.[30]

- Urbanization is having significant local impacts on weather and climate. Land-cover changes associated with urbanization are creating higher air temperatures compared to the surrounding rural area.[31,32] This is known as the "urban heat island" effect (see Ch. 9: Human Health). Urban landscapes are also affecting formation of convective storms and changing the location and amounts of precipitation compared to pre-urbanization.[32,33]

- Land-use and land-cover changes are affecting global atmospheric concentrations of greenhouse gases. The impact is expected to be most significant in areas with forest loss or gain, where the amount of carbon that can be transferred from the atmosphere to the land (or from the land to the atmosphere) is modified. Even in relatively un-forested areas, this effect can be significant. A recent USGS report suggests that from 2001 to 2005 in the Great Plains between 22 to 106 million metric tons of carbon were stored in the biosphere due to changes in land use and climate.[34] Even with these seemingly large numbers, U.S. forests absorb only 7% to 24% (with a best estimate of 16%) of fossil fuel CO_2 emissions (see Ch. 15: Biogeochemical Cycles, "Estimating the U.S. Carbon Sink").

Key Message 3: Adapting to Climate Change

Individuals, businesses, non-profits, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.

Land-use and land-cover patterns may be modified to adapt to anticipated or observed effects of a changed climate. These changes may be either encouraged or mandated by government (whether at federal or other levels), or undertaken by private initiative. In the U.S., even though land-use decisions are highly decentralized and strongly influenced by Constitutional protection of private property, the Supreme Court has also defined a role for government input into some land-use decisions.[35] Thus on the one hand farmers may make private decisions to plant different crops in response to changing growing conditions and/or market prices. On the other hand, homeowners may be compelled to respond to policies, zoning, or regulations (at national, state, county, or municipal levels) by elevating their houses to reduce flood impacts associated with more intense rainfall events and/or increased impervious surfaces.

Land-use and land-cover changes are thus rarely the product of a single factor. Land-use decision processes are influenced not only by the biophysical environment, but also by markets, laws, technology, politics, perceptions, and culture. Yet there is evidence that climate adaptation considerations are playing an increasingly large role in land decisions, even in the absence of a formal federal climate policy. Motivations typically include avoiding or reducing negative impacts from extreme weather events (such as storms or heat waves) or from slow-onset hazards (such as sea level rise) (see Ch. 12: Indigenous Peoples).

For example, New Orleans has, through a collection of private and public initiatives, rebuilt some of the neighborhoods damaged by Hurricane Katrina with housing elevated six feet or even higher above the ground and with roofs specially designed to facilitate evacuation.[36] San Francisco has produced a land-use plan to reduce impacts from a rising San Francisco Bay.[37] A similar concern has prompted collective action in four Miami-area counties and an array of San Diego jurisdictions, to name just two locales, to shape future land uses to comply with regulations linked to sea level rise projections.[36,38] Chicago has produced a plan for limiting the number of casualties, especially among the elderly and homeless, during heat waves (Ch. 9: Human Health).[36] Deeper discussion of the factors commonly influencing adaptation decisions at household, municipal, state, and federal levels is provided in Chapter 28 (Ch. 28: Adaptation) of this report; Chapters 26 (Ch. 26: Decision Support) and 27 (Ch. 27: Mitigation) treat the related topics of Decision Support and Mitigation, respectively.

Key Message 4: Reducing Greenhouse Gas Levels

Choices about land use and land management may provide a means of reducing atmospheric greenhouse gas levels.

Choices about land use and land management affect the amount of greenhouse gases entering and leaving the atmosphere and, therefore, provide opportunities to reduce climate change (Ch. 15: Biogeochemical Cycles; Ch. 27: Mitigation).[39] Such choices can affect the balance of these gases directly, through decisions to preserve or restore carbon in standing vegetation (like forests) and soils, and indirectly, in the form of land-use policies that affect fossil fuel emissions by influencing energy consumption for transportation and in buildings. Additionally, as crops are increasingly used to make fuel, the potential for reducing net carbon emissions through replacement of fossil fuels represents a possible land-based carbon emissions reduction strategy, albeit one that is complicated by many natural and economic interactions that will determine the ultimate effect of these strategies on emissions (Ch. 7: Forests; Ch. 6: Agriculture).

Land-cover change and management accounts for about one-third of all carbon released into the atmosphere by people globally since 1850. The primary source related to land use has been the conversion of native vegetation like forests and grasslands to croplands, which in turn has released carbon from vegetation and soil into the atmosphere as carbon dioxide (CO_2).[40] Currently, an estimated 16% of CO_2 going into the atmosphere is due to land-related activities globally, with the remainder coming from fossil fuel burning and cement manufacturing.[40] In the United States, activities related to land use are effectively balanced with respect to CO_2: as much CO_2 is released to the atmosphere by land-use activities as is taken up by and stored in, for example, vegetation and soil. The regrowth of forests and increases of conservation-related forest and crop management practices have also increased carbon storage. Overall, setting aside emissions due to burning fossil fuels, in the U.S. and the rest of North America, land cover takes up more carbon than it releases. This has happened as a result of more efficient forest and agricultural management practices, but it is not clear if this rate of uptake can be increased or if it will persist into the future. The projected declines in forest area (Figure 13.3) put these carbon stores at risk. Additionally, the rate of carbon uptake on a given acre of forest can vary with weather, making it potentially sensitive to climate changes.[41]

Opportunities to increase the net uptake of carbon from the atmosphere by the land include[42] increasing the amount of area in ecosystems with high carbon content (by converting farms to forests or grasslands); increasing the rate of carbon uptake in existing ecosystems (through fertilization); and reducing carbon loss from existing ecosystems (for example, through no-till farming).[43] Because of these effects, policies specifically aimed at increasing carbon storage, either directly through mandates or indirectly through a market for carbon offsets, may be used to encourage more land-based carbon storage.[44]

The following uncertainties deserve further investigation: 1) the effects of these policies or actions on the balance of other greenhouse gases, like methane and nitrous oxide; 2) the degree of permanence these carbon stores will have in a changing climate (especially through the effects of disturbances like fires and plant pests[45]); 3) the degree to which increases in carbon storage can be attributed to any specific policy, or whether or not they may have occurred without any policy change; and 4) the possibility that increased carbon storage in one location might be partially offset by releases in another. All of these specific mitigation options present implementation challenges, as the decisions must be weighed against competing objectives. For example, retiring farmland to sequester carbon may be difficult to achieve if crop prices rise,[46] such as has occurred in recent years in response to the fast-growing market for biofuels. Agricultural research and development that increases the productivity of the sector presents the possibility of reducing demand for agricultural land and may serve as a powerful greenhouse gas mitigation strategy, although the ultimate net effect on greenhouse gas emissions is uncertain.[47]

Land-use decisions in urban areas also present carbon reduction options. Carbon storage in urban areas can reach densities as high as those found in tropical forests, with most of that carbon found in soils, but also in vegetation, landfills, and the structures and contents of buildings.[48] Urban and suburban areas tend to be net sources of carbon to the atmosphere, whereas exurban and rural areas tend to be net sinks.[49] Effects of urban development patterns on carbon storage and emissions due to land and fossil fuel use are topics of current research and can be affected by land-use planning choices. Many cities have adopted land-use plans with explicit carbon goals, typically targeted at reducing carbon emissions from the often intertwined activities of transportation and energy use. This trend, which includes major cities such as Los Angeles,[50] Chicago,[51] and New York City[52] as well as small towns, such as Homer, Alaska,[53] has occurred even in the absence of a formal federal climate policy.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

The author team benefited from a number of relevant technical input reports. One report described the findings of a three-day workshop held from November 29 to December 1, 2011, in Salt Lake City, in which a number of the chapter authors participated.2 Findings of the workshop provided a review of current issues and topics as well as the availability and quality of relevant data. In addition, from December 2011 through June 2012 the author team held biweekly teleconferences. Key messages were identified during this period and discussed in two phases, associated with major chapter drafts. An early draft identified a number of issues and key messages. Based on discussions with National Climate Assessment (NCA) leadership and other chapter authors, the Land Use and Land Cover Change authors identified and reached consensus on a final set of four key messages and organized most of the chapter to directly address these messages. The authors selected key messages based on the consequences and likelihood of impacts, the implied vulnerability, and available evidence. Relevance to decision support, mitigation, and adaptation was also an important criterion for the selection of key messages for the cross-cutting and foundational topic of this chapter.

The U.S. acquires, produces, and distributes substantial data that characterize the nation's land cover and land use. Satellite observations, with near complete coverage over the landscape and consistency for estimating change and trends, are particularly valuable. Field inventories, especially of agriculture and forestry, provide very reliable data products that describe land cover as well as land-use change. Together, remote sensing and field inventory data, as well as related ecological and socioeconomic data, allow many conclusions about land-use and land-cover change with very high confidence.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.

Description of evidence base

The influences of climate on vegetation and soils, and thus on land cover and land use, are relatively well understood, and a number of well-validated mathematical models are used to investigate potential consequences of climate change for ecosystem processes, structure, and function. Given scenarios about socioeconomic factors or relevant models, some aspects of land-use and land-cover change can also be analyzed and projected into the future based on assumed climate change. During a workshop convened to review land-use and land-cover change for the NCA, participants summarized various studies from different perspectives, including agriculture and forestry as well as socioeconomic issues such as flood insurance.[2]

Residential exposure to wildfire is an excellent example supporting this key message and is well documented in the literature.[16,17,18]

New information and remaining uncertainties

Steadily accumulating field and remote sensing observations as well as inventories continue to increase confidence in this key message. A recent study by the EPA[13] provides relevant projections of housing density and impervious surface under alternative scenarios of climate change.

While there is little uncertainty about the general applicability of this key message, the actual character and consequences of climate change as well as its interactions with land cover and land use vary significantly between locations and circumstances. Thus the specific vulnerabilities resulting from the specific ways in which people, both as individuals and as collectives, will respond to anticipated or observed climate change impacts are less well understood than the biophysical dimensions of this problem.

Assessment of confidence based on evidence

Very High. Observed weather and climate impacts and consequences for land cover and land use, basic understanding of processes and analyses using models of those processes, as well as substantial literature are consistent in supporting this key message.

KEY MESSAGE#2 TRACEABLE ACCOUNT

Land-use and land-cover changes affect local, regional, and global climate processes.

Description of evidence base

The dependence of weather and climate processes on land surface properties is reasonably well understood in terms of the biophysical processes involved. Most climate models represent land-surface conditions and processes, though only recently have they begun to incorporate these conditions dynamically to represent changes in the land surface within a model run. Regional weather models are increasingly incorporating land surface characteristics. Extensive literature – as well as textbooks – documents this understanding, as do models of land surface processes and properties. A Technical Input report to the National Climate Assessment[1] summarizes the literature and basic understanding of interactions between the atmosphere and land surface that influence climate.

Examples are provided within the chapter to demonstrate that land-use and land-cover change are affecting U.S. climate.[20,24,25,27,31,32,33,34]

New information and remaining uncertainties

While there is little uncertainty about this key message in general, the heterogeneity of the U.S. landscape and associated processes, as well as regional and local variations in atmospheric processes, make it difficult to analyze or predict the character of land use and land cover influences on atmospheric processes at all scales.

Assessment of confidence based on evidence

Very High. The basic processes underlying the biophysics of interactions between the land surface and atmosphere are well understood. A number of examples and field studies are consistent in demonstrating effects of land use and land-cover change on the climate of the United States.

Key message #3 Traceable Account

Individuals, businesses, non-profits, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.

Description of evidence base

The key message is supported by well-understood aspects of land-use planning and management, including the legal roles of government and citizens and management practices such as zoning and taxation. Participants in the NCA workshop (Nov 29-Dec 1, 2011, in Salt Lake City) on land use and land cover presented and discussed a number of examples showing the influences of land-use decisions on climate change adaptation options.[2] The chapter describes specific examples of measures to adapt to climate change, further supporting this key message.[36,37,38]

New information and remaining uncertainties

Experience with climate change adaptation measures involving land-use decisions is accumulating rapidly.[36,37,38] Although there is little uncertainty that land-use decisions can enable adaptation to climate change, the information about climate change, at scales where such decisions are made, is generally lacking.

Assessment of confidence based on evidence

Very High. The aspects of land-use planning that can enable climate change adaptation are well understood and examples demonstrate where actions are being taken.

Key message #4 Traceable Account

Choices about land use and land management provide a means of reducing atmospheric greenhouse gas levels.

Description of evidence base

The evidence base for this key message includes scientific studies on the carbon cycle at both global and local scales (summarized in Izzauralde et al. 2013; Hurteau 2013; and Cambardella and Hatfield 2013).[42,43,45] The evidence base also includes policy studies on the costs and benefits and feasibilities of various actions to reduce carbon emissions from land-based activities and/or to increase carbon storage in the biosphere through land-based activities (summarized in Jones et al. 2013; and Pearson and Brown 2013).[44] Foundational studies are summarized in the NCA Technical Input documents.[1,2]

New information and remaining uncertainties

A major study by the U.S. Geological Survey is estimating carbon stocks in vegetation and soils of the U.S., and this inventory will

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

clarify the potential for capturing greenhouse gasses by land-use change (an early result is reported in Sohl et al. 2012[14]).

There is little uncertainty behind the premise that specific land uses affect the carbon cycle. There are, however, scientific uncertainties regarding the magnitudes of effects resulting from specific actions designed to leverage this linkage for mitigation. For example, uncertainties are introduced regarding the permanence of specific land-based stores of carbon, the incremental value of specific management or policy decisions to increase terrestrial carbon stocks beyond changes that would have occurred in the absence of management, and the possibility for decreases in carbon storage in another location that offset increases resulting from specific actions at a given location. Also, we do not yet know how natural processes might alter the amount of carbon storage expected to occur with management actions. There are further uncertainties regarding the political feasibilities and economic efficacy of policy options to use land-based activities to reduce the concentration of greenhouse gases in the atmosphere.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **medium** confidence that land use and land management choices can reduce the amount of greenhouse gases in the atmosphere.

Climate Change Impacts in the United States

CHAPTER 14
RURAL COMMUNITIES

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On the Web: http://nca2014.globalchange.gov/report/sectors/rural-communities

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

14 RURAL COMMUNITIES

KEY MESSAGES

1. **Rural communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.**
2. **Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.**
3. **Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.**

More than 95% of U.S. land area is classified as rural, but is home to just 19% of the population (see also Ch. 13: Land Use & Land Cover Change).[1] Rural America's importance to the country's economic and social well-being is disproportionate to its population, as rural areas provide natural resources that much of the rest of the United States depends on for food, energy, water, forests, recreation, national character, and quality of life.[2] Rural economic foundations and community cohesion are intricately linked to these natural systems, which are inherently vulnerable to climate change. Urban areas that depend on goods and services from rural areas will also be affected by climate change driven impacts across the countryside.

Warming trends, climate volatility, extreme weather events, and environmental change are already affecting the economies and cultures of rural areas. Many rural communities face considerable risk to their infrastructure, livelihoods, and quality of life from observed and projected climate shifts (Ch. 12: Indigenous Peoples). These changes will progressively increase volatility in food commodity markets, shift the ranges of plant and animal species, and, depending on the region, increase water scarcity, exacerbate flooding and coastal erosion, and increase the intensity and frequency of wildfires across the rural landscape.

Climate changes will severely challenge many rural communities, shifting locations where particular economic activities are capable of thriving. Changes in the timing of seasons, temperatures, and precipitation will alter where commodities, value-added crops, and recreational activities are best suited. Because many rural communities are less diverse than urban areas in their economic activities, changes in the viability of one traditional economic sector will place disproportionate stresses on community stability.

Climate change impacts will not be uniform or consistent across rural areas, and some communities may benefit from climate change. In the short term, the U.S. agricultural system is expected to be fairly resilient to climate change due to the system's flexibility to engage in adaptive behaviors such as expansion of irrigated acreage, regional shifts in acreage for specific crops, crop rotations, changes to management decisions (such as choice and timing of inputs and cultivation practices), and altered trade patterns compensating for yield changes (Ch.


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6: Agriculture; Key Message 5).[4] Recreation, tourism, and leisure activities in some regions will benefit from shifts in temperature and precipitation.

Negative impacts from projected climate changes, however, will ripple throughout rural America. Agricultural systems in some areas may need to undergo more transformative changes to keep pace with future climate change (Ch. 6: Agriculture, Key Message 5). In lakes and riparian areas, warming is projected to increase the growth of algae and invasive species, particularly in areas already facing water quality impairments.[5] Mountain species and cold water fish, such as salmon, are expected to face decreasing range sizes due to warming, while ranges could expand for some warm water fish, such as bass.[6] Alaska, with its reliance on commercial and subsistence fishing catch, is particularly vulnerable. Warmer weather and higher water temperatures will reduce salmon harvests, creating hardships for the rural communities and tribes that depend upon these catches (Ch. 12: Indigenous Peoples, Key Message 1).[7] Communities in Guam and American Samoa, which depend on fish for 25% to 69% of their protein, are expected to be particularly hard hit as climate change alters the composition of coral reef ecosystems.[8]

Across the United States, rural areas provide ecosystem services – like carbon absorption in forests, water filtration in wetlands, wildlife habitat in prairies, and environmental flows in rivers and streams – whose value tends to be overlooked. Preserving these ecosystem services sustains the quality of life in rural communities and also benefits those who come to rural communities for second homes, tourism, and other amenities. They also provide urban residents with vital resources – like food, energy, and fresh water – that meet essential needs. This layered connection between rural areas and populous urban centers suggests that maintaining the health of rural areas is a national, and not simply a local, concern.

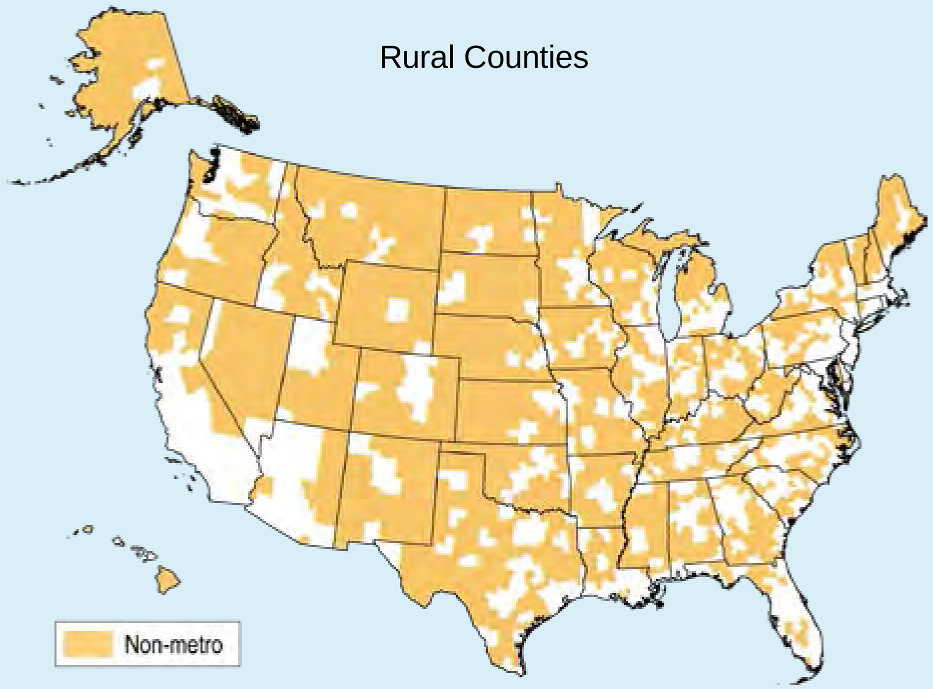

Figure 14.1. Although the majority of the U.S. population lives in urban areas, most of the country is still classified as rural. In this map, counties are classified as rural if they do not include any cities with populations of 50,000 or more. (Figure source: USDA Economic Research Service 2013[3]).

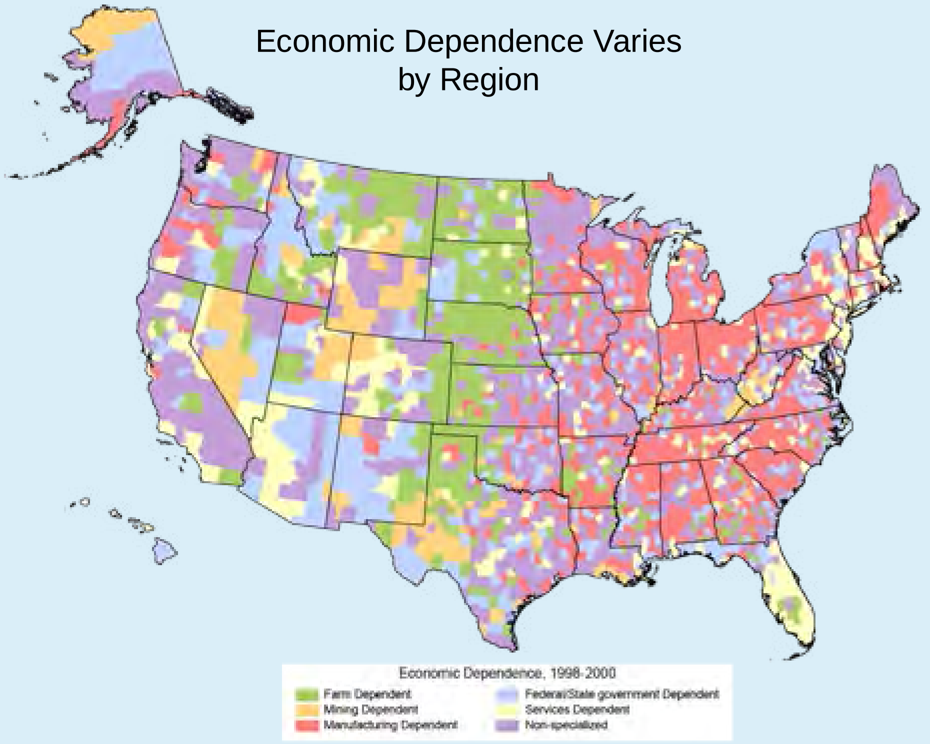

Figure 14.2. Much of the rural United States depends on agriculture, mining, and manufacturing. Climate changes will affect each region and each economic sector in complex and interrelated ways. The economic dependence classification used in the map indicates the largest share of earnings and employment in each county. (Figure source: USDA Economic Research Service 2013[3]).

Key Message 1: Rural Economies

Rural communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.

River flood waters illustrate threats rural areas face in a changing climate.

Rural America has already experienced some of the impacts of climate change related weather effects, including crop and livestock loss from severe drought and flooding,[9] infrastructure damage to levees and roads from extreme storms,[10] shifts in planting and harvesting times in farming communities,[11] and large-scale losses from fires and other weather-related disasters.[12] These impacts have profound effects, often significantly affecting the health and well-being of rural residents as well as their communities, and are amplified by the essential economic link that many of these communities have to their natural resource base.

Rural communities are often characterized by their natural resources and associated economic activity. Dominant economic drivers include agriculture, forestry, mining, energy, outdoor recreation, and tourism. In addition, many rural areas with pleasant climates and appealing landscapes are increasingly reliant on second-home owners and retirees for their tax base and community activities.

Nationally, fewer than 7% of rural workers are directly employed in agriculture, but the nation's two million farms occupy more than 40% of U.S. land mass – and many rural

Growing Season Lengthens

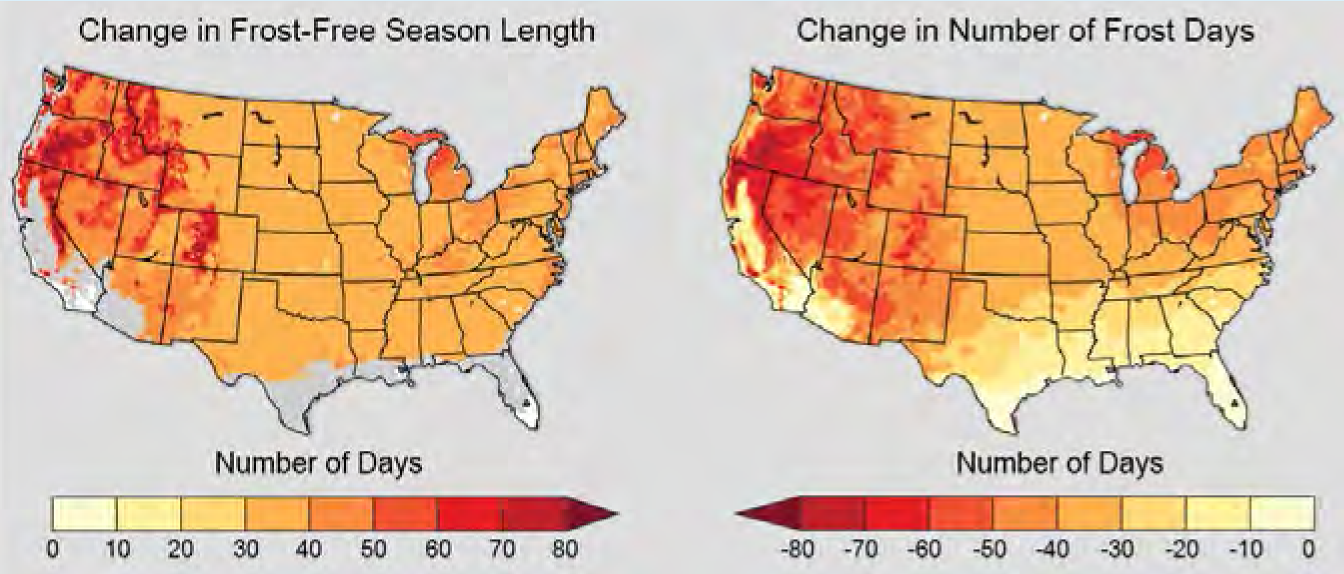

Figure 14.3. The left map shows that if emissions continue to increase (A2 scenario), the U.S. growing season (or frost-free season) will lengthen by as much as 30 to 80 days by the end of the century (2070-2099 as compared to 1971-2000). The right map shows a reduction in the number of frost days (days with minimum temperatures below freezing) by 20 to 80 days in much of the United States in the same time period. While changes in the growing season may have positive effects for some crops, reductions in the number of frost days can result in early bud-bursts or blooms, consequently damaging some perennial crops grown in the United States (See also Ch. 6: Agriculture). White areas are projected to experience no freezes for 2070-2099, and gray areas are projected to experience more than 10 freeze-free years during the same period. (Figure source: NOAA NCDC / CICS-NC).

communities rely extensively on farming and ranching (Ch. 6 Agriculture; Ch. 13 Land Use & Land Cover Change).[13] Farmers are responding to climate change by shifting cropping patterns and altering the timing of planting and harvesting. This may result in additional use of herbicides and pesticides with the accompanying human exposure to additional health risks.[14] Changes in rainfall, temperature, and extreme weather events will increase the risk of poor yields and reduced crop profitability. For example, the increased frequency and intensity of heavy downpours will accelerate soil erosion rates, increasing deposition of nitrogen and phosphorous into water bodies and diminishing water quality.[15]

Many areas will face increasing competition for water among household, industrial, agricultural, and urban users (Ch. 3: Water).[16] Reduced surface water will place more stress on surface water systems as well as groundwater systems (Ch. 3: Water; Key Message 4). In-stream flow requirements for the maintenance of environmental resources are an equally important water demand. While irrigated cropland is an important and growing component of the farm economy,[17] water withdrawals necessary for generating electricity in thermal power plants are already roughly equal to irrigation withdrawals.[18] As climate change increases water scarcity in some regions, there will be increased competition for water between energy production and agriculture.[19] Mining also requires large quantities of water, and scarcity resulting from drought associated with climate change may affect operations. Changes in seasonality and intensity of precipitation will increase costs of runoff containment. Climate change impacts on forestry have important implications for timber and forest-amenity-based rural communities. Shifting forest range and composition, as well as increased attacks from pests and diseases, will have negative effects on biodiversity and will increase wildfire risks (Ch. 7: Forests).[8,20] Shifts in the distribution and abundance of many economically important tree species would affect the pulp and wood industry. As ranges shift and the distribution of plant species in forests changes, the range of other forest-dependent animal species will also change, causing additional economic and sociocultural impacts.

Tourism contributes significantly to rural economies. Changes in the length and timing of seasons, temperature, precipitation, and severe weather events can have a direct impact on tourism and recreation activities by influencing visitation patterns and tourism-related economic activity.

Climate change impacts on tourism and recreation will vary significantly by region. For instance, some of Florida's top tourist attractions, including the Everglades and Florida Keys, are threatened by sea level rise,[21] with estimated revenue losses of $9 billion by 2025 and $40 billion by the 2050s. The effects of climate change on the tourism industry will not be exclusively negative. In Maine, coastal tourism could increase due to warmer summer months, with more people visiting the state's beaches.[22] Employing a Tourism Climatic Index (Figure 14.4) that accounts for temperature, precipitation, sunshine, and wind, one study finds that conditions conducive for outdoor recreation will be shifting northward with climate change, though it is unclear whether absolute conditions or relative weather conditions will be more important in influencing future tourist behaviors.[23]

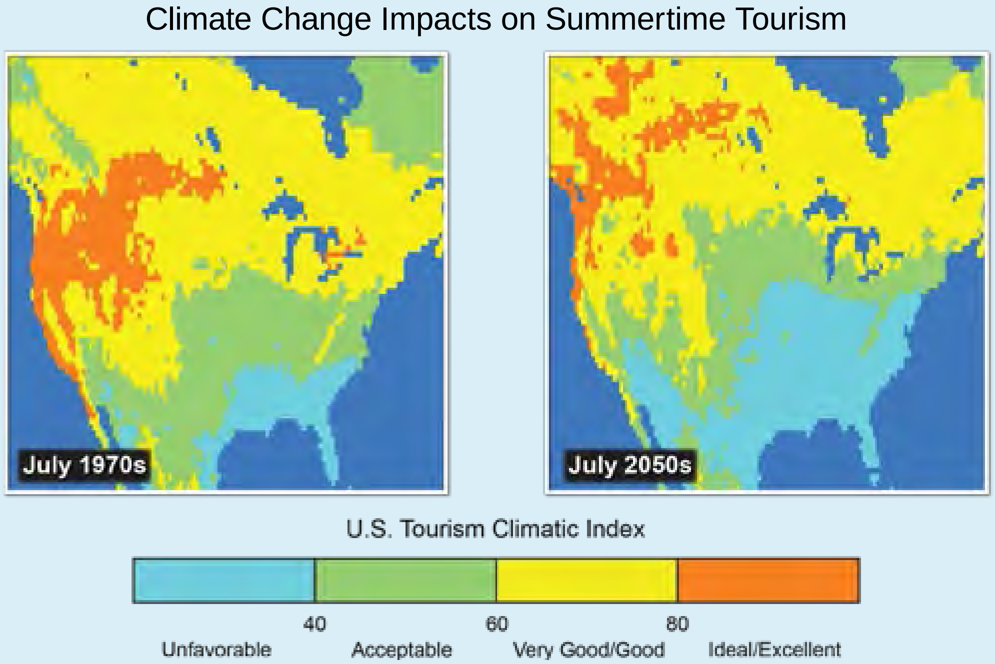
Climate Change Impacts on Summertime Tourism

Figure 14.4. Tourism is often climate-dependent as well as seasonally dependent. Increasing heat and humidity – projected for summers in the Midwest, Southeast, and parts of the Southwest by mid-century (compared to the period 1961-1990) – is likely to create unfavorable conditions for summertime outdoor recreation and tourism activity. The figures illustrate projected changes in climatic attractiveness (based on maximum daily temperature and minimum daily relative humidity, average daily temperature and relative humidity, precipitation, sunshine, and wind speed) in July for much of North America. In the coming century, the distribution of these conditions is projected to shift from acceptable to unfavorable across most of the southern Midwest and a portion of the Southeast, and from very good or good to acceptable conditions in northern portions of the Midwest, under a high emissions scenario (A2a). (Figure source: Nicholls et al. 2005[24]).

Climate change will also influence the distribution and composition of plants and animals across the United States. Hunting, fishing, bird watching, and other wildlife-related activities will be affected as habitats shift and relationships among species change.[25] Cold-weather recreation and tourism will be adversely affected by climate change. Snow accumulation in the western United States has decreased, and is expected to continue to decrease, as a result of observed and projected warming. Reduced snow accumulation also reduces the amount of spring snowmelt, decreasing warm-season runoff in mid- to high-latitude regions.

Similar changes to snowpack are expected in the Northeast.[26] Adverse impacts on winter sports are projected to be more pronounced in the Northeast and Southwest regions of the United States.[8] Coastal areas will be adversely affected by sea level rise and increased severity of storms.[22,27] Changing environmental conditions, such as wetland loss and beach erosion in coastal areas[28] and increased risk of natural hazards such as wildfire, flash flooding, storm surge, river flooding, drought, and extremely high temperatures can alter the character and attraction of rural areas as tourist destinations.

The implications of climate change on communities that are dependent on resource extraction (coal, oil, natural gas, and mining) have not been well studied. Attributes of economic development in these communities, such as cyclical growth, transient workforce, rapid development, pressure on infrastructure, and lack of economic diversification suggest that these communities could face challenges in adapting to climate change.[13,29,30]

Key Message 2: Responding to Risks

Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.

Relatively rapid changes in demographics, economic activity, and climate are particularly challenging in rural communities, where local, agrarian values often run generations deep. Changing rural demographics, influenced by new immigration patterns, fluctuating economic conditions, and evolving community values add to these challenges – especially with regard to climate changes.

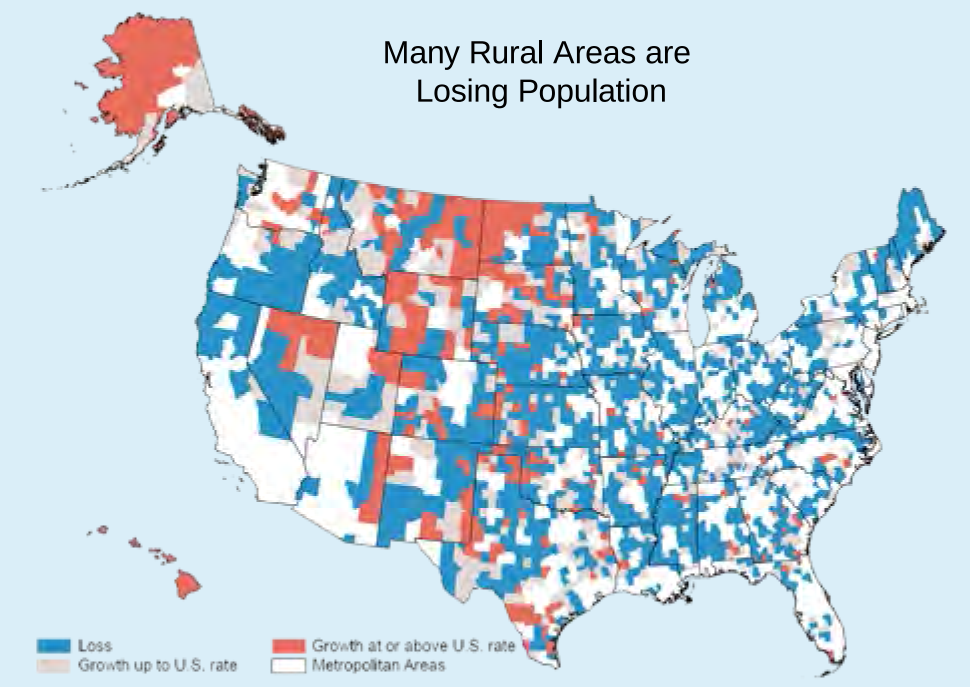

Figure 14.5. Census data show significant population decreases in many rural areas, notably in the Great Plains. Many rural communities' existing vulnerabilities to climate change, including physical isolation, reduced services like health care, and an aging population, are projected to increase as population decreases. (Figure source: USDA Economic Research Service 2013[3]).

Modern rural populations are generally older, less affluent, and less educated than their urban counterparts. Rural areas are characterized by higher unemployment, more dependence on government transfer payments, less diversified economies, and fewer social and economic resources needed for resilience in the face of major changes.[8,31] In particular, the combination of an aging population and poverty increases the vulnerability of rural communities to climate fluctuations.

There has been a trend away from manufacturing, resource extraction, and farming to amenity-based economic activity in many rural areas of the United States.[32] Expanding amenity-based economic activities in rural areas include recreation and leisure, e-commuting residents, tourism, and second home and retirement home development. This shift has stressed traditional cultural values[33] and put pressure on infrastructure[34] and natural amenities[35] that draw people to rural areas. Changes in climate and weather are likely to increase these stresses. Rural components of transportation systems are particularly vulnerable to risks from flooding and sea level rise.[36] Since rural areas often have fewer transportation options and fewer infrastructure redundancies, any disruptions in road, rail, or air transport will deeply affect rural communities.

Power and communication outages resulting from extreme events often take longer to repair in rural areas, contributing to the isolation and vulnerability of elderly residents who may not have cell phones. The lack of cellular coverage in some rural areas can create problems for emergency response during power failures.[37]

In some parts of the country there has been a recent trend in Hispanic population growth in rural regions that have not been traditional migrant destinations. New Hispanic immigrants are often highly segregated residentially and isolated from mainstream institutions,[38] making them more vulnerable to changes in climate. Low wages, unstable work, language barriers, and inadequate housing are critical obstacles to managing climate risk.

Rural communities rely on various transportation modes, both for export and import of critical goods (Ch. 5: Transportation). Climate changes will result in increased erosion and maintenance costs for local road and rail systems, as well as changes in streamflows and predictability that will result in increased maintenance costs for waterways. More frequent disruption of shipping is projected, with serious economic consequences. For example, in 2010, about 40 million tons of cereal grains were shipped by water to Louisiana, while less than 4 million tons traveled by rail.[10] While rail can help ameliorate small-scale or off-peak capacity limitations on the Mississippi River, it seems unlikely that the rail system can fully replace the river system in the event of a prolonged harvest-time disruption. Events that affect both rail and barge traffic would be particularly damaging to rural communities that depend upon these systems to get commodities to market.

Health and emergency response systems also face additional demands from substantial direct and indirect health risks associated with global climate changes. Indirect risks, particularly those posed by emerging and reemerging infectious diseases, are more difficult to assess, but pose looming threats to economically challenged communities where health services are limited. Direct threats (such as extreme heat, storm events, and coastal and riparian flooding) tend to be more associated with specific local vulnerabilities, so the risks are somewhat easier to assess.[39]

The socioeconomic and demographic characteristics of rural areas interact with climate change to create health concerns that differ from those of urban and suburban communities. Older populations with lower income and educational levels in rural areas spend a larger proportion of their income on health care than their urban counterparts. Moreover, health care access declines as geographic isolation increases. Overall, rural residents already have higher rates of age-adjusted mortality, disability, and chronic disease than do urban populations.[40] These trends are likely to be exacerbated by climate change (Ch. 9: Human Health).

Governments in rural areas are generally ill-prepared to respond quickly and effectively to large-scale events, although individuals and voluntary associations often show significant resilience. Health risks are exacerbated by limitations in the health service systems characteristic of rural areas, including the distance between rural residents and health care providers and the reduced availability of medical specialists.

The effects of climate change on mental health merit special consideration. Rural residents are already at a heightened risk from mental health issues because of the lack of access to mental health providers. The adverse impact of severe weather disasters on mental health is well established,[41] and there is emerging evidence that climate change in the form of increasing heat waves and droughts has harmful effects on mental health (Ch. 9: Human Health, Key Message 1). Droughts often result in people relocating to seek other employment, causing a loss of home and social networks. Studies have shown that springtime droughts in rural areas cause a decrease in life satisfaction.[42] The primary care physicians who form the backbone of rural health care often have heavy caseloads and lack specialized training in mental health issues.[40] Additionally, patients referred to mental health specialists often experience significant delays.[43]

The frequency and distribution of infectious diseases is also projected to increase with rising temperatures and associated seasonal shifts. Increased rates of mutation and increased resistance to drugs and other treatments are already evident in the behavior of infectious disease-causing bacteria and viruses.[44] In addition, changes in temperature, surface water, humidity, and precipitation affect the distribution and abundance of disease-carriers and intermediate hosts, and result in larger distributions for many parasites and diseases. Rural residents who spend significant time outdoors have an increased risk of exposure to these disease-carriers, like ticks and mosquitoes (Ch. 9: Human Health).

Key Message 3: Adaptation

Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.

Climate variability and increases in temperature, extreme events (such as storms, floods, heat waves, and droughts), and sea level rise are expected to have widespread impacts on the provision of services from state, regional, local, and tribal governments. Emergency management, energy use and distribution systems, transportation and infrastructure planning, and public health will all be affected.

Rural governments often depend heavily on volunteers to meet community challenges like fire protection or flood response. In addition, rural communities have limited locally available financial resources to help deal with the effects of climate change. Small community size tends to make services expensive or available only by traveling some distance.

Local governance structures tend to de-emphasize planning capacity, compared to urban areas. While 73% of metropolitan counties have land-use planners, only 29% of rural counties not adjacent to a metropolitan county had one or more planners. Moreover, rural communities are not equipped to deal with major infrastructure expenses.[45]

Communities across the United States are experiencing infrastructure losses, water scarcity, unpredictable water availability, and increased frequency and intensity of wildfires. However, local authorities often do not explicitly associate these observed changes with climate, and responses rarely take climate disruption into account. Even in communities where there is increasing awareness of climate change and interest in comprehensive adaptation planning, lack of funding, human resources, access to information, training, and expertise provide significant barriers for many rural communities.[46]

If rural communities are to respond adequately to future climate changes, they will likely need help assessing their risks and vulnerabilities, prioritizing and coordinating projects, funding and allocating financial and human resources, and deploying information-sharing and decision support tools (Ch. 26: Decision Support). There is still little systematic research on the vulnerability of rural communities and there is a need for additional empirical research in this area. Impacts due to climate change will cross community and regional lines, making solutions dependent upon meaningful participation of numerous stakeholders from federal, state, local, and tribal governments, science and academia, the private sector, non-profit organizations, and the general public (Ch. 28: Adaptation, Key Message 3).

Effective adaptation measures are closely tied to specific local conditions and needs and take into account existing social networks.[47,48] The economic and social diversity of rural communities affects the ability of both individuals and communities to adapt to climate changes, and underscores the need to assess climate change impacts on a local basis. The quality and availability of natural resources, legacies of past use, and changing industrial needs affect the economic, environmental, and social conditions of rural places and are critical factors to be assessed.[13,30,49] Successful adaptation to climate change requires balancing immediate needs with long-term development goals, as well as development of local-level capacities to deal with climate change.[48,50]

Potential national climate change mitigation responses (Ch. 27: Mitigation) – especially those that require extensive use of land, such as permanent reforestation, constructing large solar or wind arrays, hydroelectric generation, and biofuel cropping – are also likely to significantly affect rural communities, with both positive and negative effects.[51] As with the development of rural resource-intensive economic activities, where national or multi-national companies tend to wield ownership and control, local residents and communities are unlikely to be the primary investors in or beneficiaries of this kind of new economic activity. For example, mitigation policies that affect coal production could have a substantial economic impact on many rural communities, as could policies to promote production of non-fossil-fuel energy such as wind.

Decisions regarding adaptation responses for both urban and rural populations can occur at various scales (federal, state, local, tribal, private sector, and individual) but need to take interdependencies into account. Many decisions that significantly affect rural communities may not be under the control of local governments or rural residents. Given that timing is a critical aspect of adaptation, as well as mitigation, engaging rural residents early in decision processes about investments in public infrastructure, protection of shorelines, changes in insurance provision, or new management initiatives can influence individual behavior and choice in ways that enhance positive outcomes of adaptation and mitigation.

LOCAL RESPONSES TO CLIMATE CHANGE IN THE SAN JUAN MOUNTAINS

The San Juan Mountains region straddles the southern edge of the Southern Rocky Mountains and the northeastern tip of the arid Southwest. The high mountain headwaters of the Rio Grande, San Juan, and major tributaries of the Upper Colorado River are critical water towers for five states: Texas, Nevada, California, Arizona, and New Mexico. The diversity of the landforms, high plateaus, steep mountains, deep canyons, and foothills leads to a complex and diverse mix of coniferous and deciduous forested landscapes.[52] County populations in the area range from 700 to 51,000 people. Population changes between 2000 and 2010 ranged from a 25% decline to an 86% increase. Public lands account for 69% of the land base.[53] Over half of the local economies are dependent upon natural resources to support tourism, minerals and natural gas extraction, and second home development.

Average annual temperatures in the San Juan Mountains have risen 1.1°F in only three decades,[54] a rate of warming greater than any other region of the United States except Alaska.[55] The timing of snowmelt has shifted two weeks earlier between 1978 and 2007, and this earlier seasonal release of water resources is of particular concern to all western states.[56] Current challenges for the region include changes in forests due to pests and diseases, intensive recreation use, fire management for natural and prescribed fires, and increasing development in the wildland-urban interface. Communities are vulnerable to changes from a warmer and drier climate that would affect the frequency and intensity of wildfires, shift vegetation and range of forest types, and increase pressures on water supplies.

In response, the San Juan Climate Initiative drew together stakeholders, including natural resource managers, community planners, elected officials, industry representatives, resource users, citizens, non-profit organizations, and scientists. By combining resources and capabilities, stakeholders have been able to accomplish much more together than if they had worked independently. For example, local governments developed a plan to reduce greenhouse gas emissions and identify strategies for adaptation, signing the U.S. Mayor's Climate Protection Agreement in 2009. Climate modelers at University of Colorado and National Center for Atmospheric Research analyzed regional trends in temperature, precipitation, snowpack, and streamflow. Researchers at Mountain Studies Institute, University of Colorado, and Fort Lewis College are partnering with San Juan National Forest to monitor alpine plant communities and changes in climate across the region, and to document carbon resources. San Juan National Forest is developing strategies for adapting to climate changes in the region related to drought, wildfire, and other potential effects. La Plata County is leading an effort to plan for sustainable transportation and food networks that will be less dependent upon carbon-based fuels, while the Mountain Studies Institute is leading citizen science programs to monitor changes to sensitive species like the American pika.

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Hiker in the San Juan mountains, Colorado.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Message:

The key messages were initially developed at a meeting of the authors in Charleston, South Carolina, in February 2012. This initial discussion was supported by a series of conference calls from March through June, 2012. These ensuing discussions were held after a thorough review of the technical inputs and associated literature, including the Rural Communities Workshop Report prepared for the NCA[57] and additional technical inputs on a variety of topics.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Rural communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Rural Communities Workshop Report.[57] Thirty one technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that the impacts of climate change are increasing is compelling and widespread. This evidence is based on historical records and observations and on global climate models, including those driven by B1 (substantial emissions reduction) and A2 (continued increases in global emissions) scenarios. This evidence is clearly summarized and persuasively referenced in the "Our Changing Climate" chapter of this Assessment and in the Scenarios developed for the NCA.[58]

The dependency of rural communities on their natural resources has been demonstrated,[13] with a number of studies showing that climate change results in crop and livestock loss,[9] infrastructure damage to levees and roads,[10] shifts in agriculture practices,[11] and losses due to disasters.[12] A number of publications project these impacts to increase, with effects on the natural environment[8,15,20] and increased competition for water between agriculture and energy.[19] Studies have projected that tourism locations in the Everglades and Florida Keys are threatened.[21] Meanwhile, Maine's tourism could increase,[22] which coincides with a projected northern shift in outdoor recreation.[23] Hunting, fishing, and bird watching will be affected by beach erosion and wetland loss,[28] and changing plant and animal habitats and inter-species relationships (see also Ch. 8: Ecosystems). Outdoor recreation and tourism in many areas in the U.S. are affected by early snowpack melt.[8,26]

New information and remaining uncertainties

Key remaining uncertainties relate to the precise magnitude, timing, and location of impacts at regional and local scales.

Assessment of confidence based on evidence

(See confidence level key on next page)

Given the evidence and uncertainties, there is **very high** confidence that rural communities are highly dependent on natural resources that are expected to be affected by climate change, especially the many communities that rely on farming, forestry or tourism for their livelihoods.

Given the evidence and uncertainties, there is **high** confidence that climate change is currently affecting rural communities.

Given the evidence and uncertainties, there is **very high** confidence that impacts will increase (see Ch 2: Our Changing Climate).

Given the evidence and uncertainties, there is **high** confidence about shifts in locations of economic activities.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Rural Communities Workshop Report.[57] Thirty one technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

With studies showing that rural communities are already stressed,[33,34,35] a number of publications have explored the barriers of rural communities to preparing and responding to climate change.[8,31] Some studies provide in-depth looks at the obstacles created by limited economic diversity[32] and an aging population.[40]

New information and remaining uncertainties

Projecting the interactions of these variables with each other and applying this analysis to local or regional realities is complex at best, with uncertainties at every level of analysis.

Assessment of confidence based on evidence

Given the evidence and uncertainties, there is **high** confidence that the obstacle of physical isolation will hamper some communities' ability to adapt or have an adequate response during extreme events.

Given the evidence and uncertainties, there is **high** confidence that the obstacle of limited economic diversity will hinder rural communities' ability to adapt.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Given the evidence and uncertainties, there is **high** confidence that the obstacle of higher poverty rates will significantly increase vulnerability of many communities from adapting properly.

Given the evidence and uncertainties, there is **high** confidence that the obstacle of an aging population will hinder some rural communities and prevent them from having an adequate response.

Given the evidence and uncertainties, there is **high** confidence that fundamental systems in rural communities are already stressed by remoteness and limited access.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Rural Communities Workshop Report.[57] Thirty one technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Rural communities are not equipped to deal with major infrastructure expenses.[45] Work has been performed illustrating the need to tie adaptation measures to specific local conditions and needs and take into account existing social networks.[47,48] Publications have shown that there are a number of critical factors to be assessed, including the quality and availability of natural resources, legacies of past use of resources, and changing industrial needs that affect economic, environmental, and social conditions.[13,30,49] Additionally, studies have expressed the requirement of accounting for both near- and long-term needs for climate change adaptation to be successful.[50]

New information and remaining uncertainties

It is difficult to fully capture the complex interactions of the entire socioeconomic-ecological system within which the effects of climate change will interact, especially in regard to local and regional impacts. Impact assessments and adaptation strategies require improved understanding of capacity and resilience at every level, international to local. The policy context in which individuals and communities will react to climate effects is vague and uncertain. Identification of informational needs alone indicates that adaptation will be expensive.

Assessment of confidence based on evidence

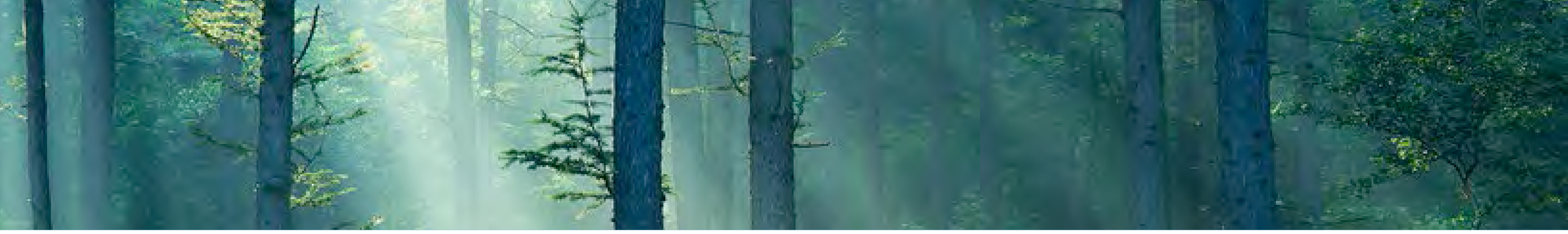
Given the evidence and uncertainties, there is **high** confidence that rural communities have limited capacity to respond to impacts, because of their remoteness, age, lack of diversity, and other reasons described in the text.

Given the evidence and uncertainties, there is **high** confidence that rural communities have limited capacity to plan for impacts, as explained in the text.

Given the evidence and uncertainties, there is **high** confidence that rural communities will have limited capacity to anticipate impacts because of the lack of infrastructure and expertise available in rural communities.

Given the evidence and uncertainties, there is **high** confidence that significant climate change adaptation is needed for transportation in rural communities.

Given the evidence and uncertainties, there is **high** confidence that significant climate change adaptation is needed for health care and emergency response in rural communities, so that rural communities can handle climate change impacts.



Climate Change Impacts in the United States

CHAPTER 15
BIOGEOCHEMICAL CYCLES

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On the Web: http://nca2014.globalchange.gov/report/sectors/biogeochemical-cycles

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

15 BIOGEOCHEMICAL CYCLES

KEY MESSAGES

1. **Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
2. **In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO_2 and other greenhouse gases.**
3. **Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.**

Biogeochemical cycles involve the fluxes of chemical elements among different parts of the Earth: from living to non-living, from atmosphere to land to sea, and from soils to plants. They are called "cycles" because matter is always conserved and because elements move to and from major pools via a variety of two-way fluxes, although some elements are stored in locations or in forms that are differentially accessible to living things. Human activities have mobilized Earth elements and accelerated their cycles – for example, more than doubling the amount of reactive nitrogen that has been added to the biosphere since pre-industrial times.[1,2] Reactive nitrogen is any nitrogen compound that is biologically, chemically, or radiatively active, like nitrous oxide and ammonia, but not nitrogen gas (N_2). Global-scale alterations of biogeochemical cycles are occurring, from human activities both in the U.S. and elsewhere, with impacts and implications now and into the future. Global carbon dioxide emissions are the most significant driver of human-caused climate change. But human-accelerated cycles of other elements, especially nitrogen, phosphorus, and sulfur, also influence climate. These elements can affect climate directly or act as indirect factors that alter the carbon cycle, amplifying or reducing the impacts of climate change.

Climate change is having, and will continue to have, impacts on biogeochemical cycles, which will alter future impacts on climate and affect our capacity to cope with coupled changes in climate, biogeochemistry, and other factors.

Key Message 1: Human-Induced Changes

Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

The human mobilization of carbon, nitrogen, and phosphorus from the Earth's crust and atmosphere into the environment has increased 36, 9, and 13 times, respectively, compared to geological sources over pre-industrial times.[3] Fossil fuel burning, land-cover change, cement production, and the extraction and production of fertilizer to support agriculture are major causes of these increases.[4] Carbon dioxide (CO_2) is the most abundant of the heat-trapping greenhouse gases that are increasing due to human activities, and its production dominates atmospheric forcing of global climate change.[5] However, methane (CH_4) and nitrous oxide (N_2O) have higher greenhouse-warming potential per molecule than CO_2, and both are also increasing in the atmosphere. In the U.S. and Europe, sulfur emissions have declined over the past three decades, especially since the mid-1990s, because of efforts to reduce air pollution.[6] Changes in biogeochemical cycles of carbon, nitrogen, phosphorus, and other elements – and the coupling of those cycles – can influence climate. In turn, this can change atmospheric composition in other ways that affect how the planet absorbs and reflects sunlight (for example, by creating small particles known as aerosols that can reflect sunlight).

State of the Carbon Cycle

The U.S. was the world's largest producer of human-caused CO_2 emissions from 1950 until 2007, when it was surpassed by China. U.S. emissions account for approximately 85% of North American emissions of CO_2[7] and 18% of global emissions.[8,9] Ecosystems represent potential "sinks" for CO_2, which are places where carbon can be stored over the short or long term (see "Estimating the U.S. Carbon Sink"). At the continental scale, there has been a large and relatively consistent increase in forest carbon stocks over the last two decades,[10] due to recovery from past forest harvest, net increases in forest area, improved forest management regimes, and faster growth driven by climate or fertilization by CO_2 and nitrogen.[7,11] The largest rates of disturbance and "regrowth sinks" are in southeastern, south central, and Pacific northwestern regions.[11] However, emissions of CO_2 from human activities in the U.S. continue to increase and exceed ecosystem CO_2 uptake by more than three times. As a result, North America remains a net source of CO_2 into the atmosphere[7] by a substantial margin.

Major North American Carbon Dioxide Sources and Sinks

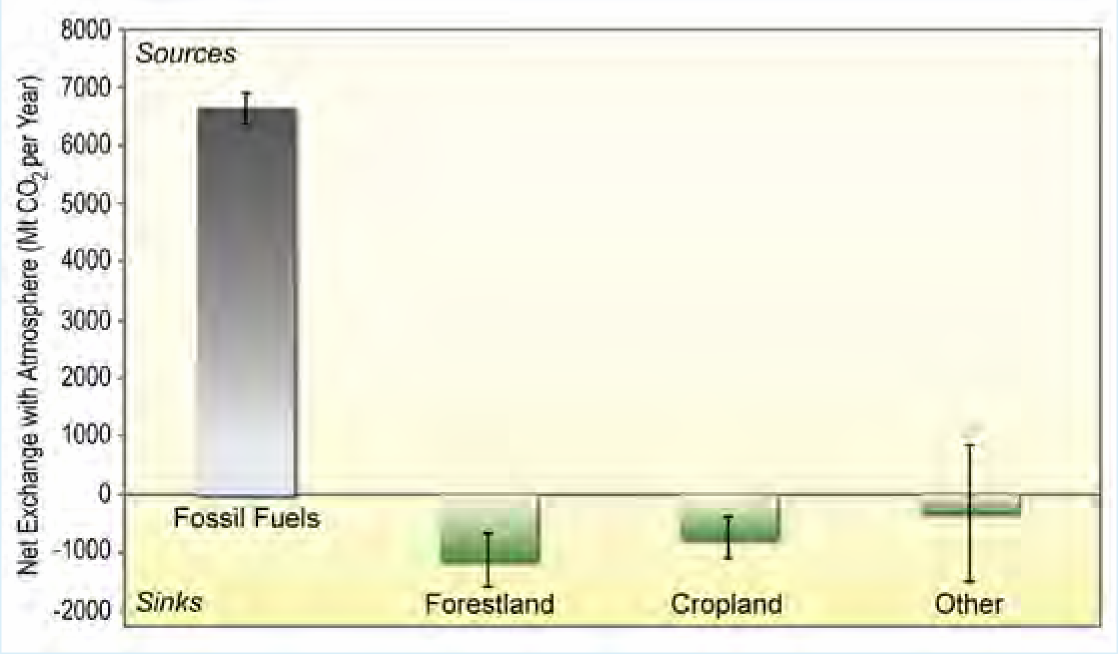

Figure 15.1. The release of carbon dioxide from fossil fuel burning in North America (shown here for 2010) vastly exceeds the amount that is taken up and temporarily stored in forests, crops, and other ecosystems (shown here is the annual average for 2000-2006). (Figure source: King et al. 2012[7]).

Sources and Fates of Reactive Nitrogen

The nitrogen cycle has been dramatically altered by human activity, especially by the use of nitrogen fertilizers, which have increased agricultural production over the past half century.[1,2] Although fertilizer nitrogen inputs have begun to level off in the U.S. since 1980,[12] human-caused reactive nitrogen inputs are now at least five times greater than those from natural sources.[13,14,15,16] At least some of the added nitrogen is converted to nitrous oxide (N_2O), which adds to the greenhouse effect in Earth's atmosphere.

An important characteristic of reactive nitrogen is its legacy. Once created, it can, in sequence, travel throughout the environment (for example, from land to rivers to coasts, sometimes via the atmosphere), contributing to environmental problems such as the formation of coastal low-oxygen "dead zones" in marine ecosystems in summer. These problems persist until the reactive nitrogen is either captured and stored in a long-term pool, like the mineral layers of soil or deep ocean sediments, or converted back to nitrogen gas.[17,18] The nitrogen cycle affects atmospheric concentrations of the three most important human-caused greenhouse gases: carbon dioxide, methane, and nitrous oxide. Increased available nitrogen stimulates the uptake of carbon dioxide by plants, the release of methane from wetland soils, and the production of nitrous oxide by soil microbes.

Human Activities that Form Reactive Nitrogen
and Resulting Consequences in Environmental Reservoirs

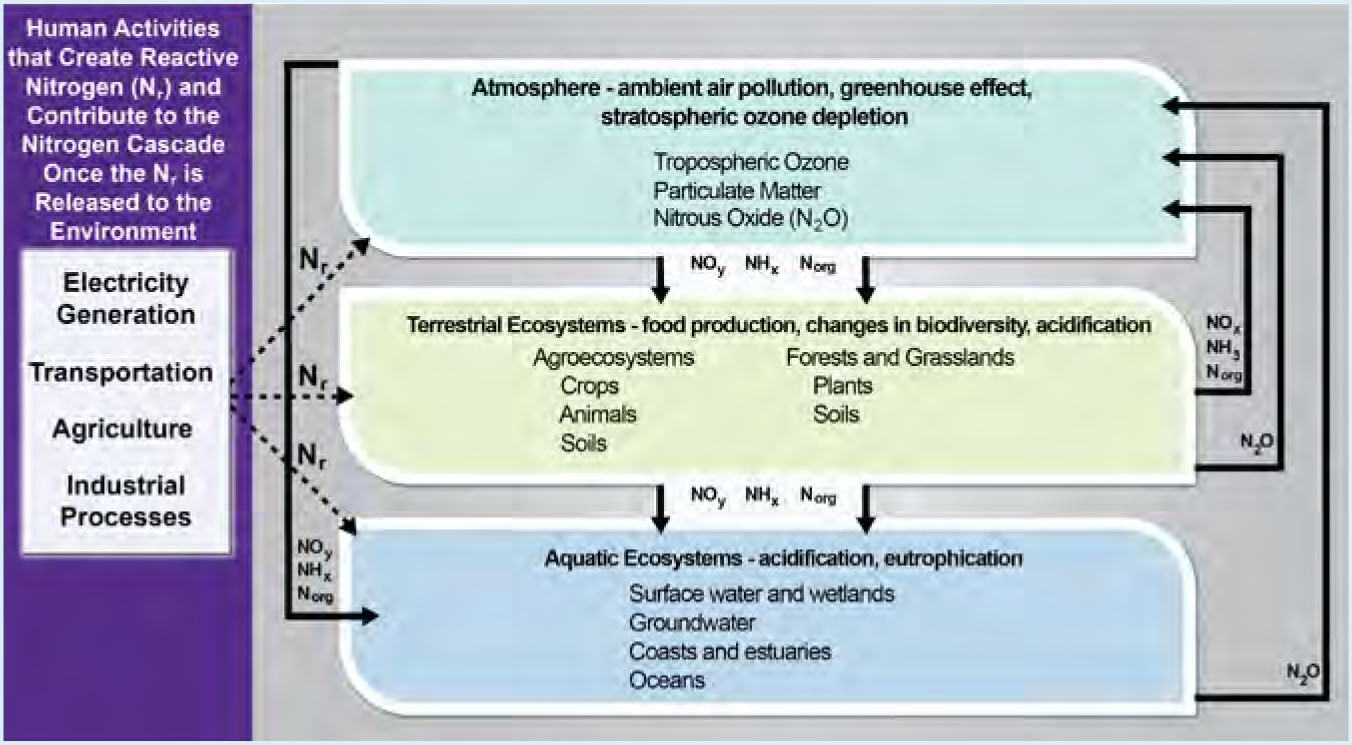

Figure 15.2. Once created, a molecule of reactive nitrogen has a cascading impact on people and ecosystems as it contributes to a number of environmental issues. Molecular terms represent oxidized forms of nitrogen primarily from fossil fuel combustion (such as nitrogen oxides, NO_x), reduced forms of nitrogen primarily from agriculture (such as ammonia, NH_3), and organic forms of nitrogen (N_{org}) from various processes. NO_y is all nitrogen-containing atmospheric gases that have both nitrogen and oxygen, other than nitrous oxide (N_2O). NH_x is the sum of ammonia (NH_3) and ammonium (NH_4). (Figure source: adapted from EPA 2011;[13] Galloway et al. 2003;[17] with input from USDA. USDA contributors were Adam Chambers and Margaret Walsh).

Phosphorus and other elements

The phosphorus cycle has been greatly transformed in the United States,[19] primarily from the use of phosphorus fertilizers in agriculture. Phosphorus has no direct effects on climate, but does have indirect effects, such as increasing carbon sinks by fertilizing plants. Emissions of sulfur, as sulfur dioxide, can reduce the growth of plants and stimulate the leaching of soil nutrients needed by plants.[20]

Key Message 2: Sinks and Cycles

In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO_2 and other greenhouse gases.

Considering the entire atmospheric CO_2 budget, the temporary net storage on land is small compared to the sources: more CO_2 is emitted than can be taken up (see “Estimating the U.S. Carbon Sink”).[7,21,22,23] Other elements and compounds affect that balance by direct and indirect means (for example, nitrogen stimulates carbon uptake [direct] and nitrogen decreases the soil methane sink [indirect]). The net effect on Earth’s energy balance from changes in major biogeochemical cycles (carbon, nitrogen, sulfur, and phosphorus) depends upon processes that directly affect how the planet absorbs or reflects sunlight, as well as those that indirectly affect concentrations of greenhouse gases in the atmosphere.

Carbon

In addition to the CO_2 effects described above, other carbon-containing compounds affect climate change, such as methane and volatile organic compounds (VOCs). As the most abundant non-CO_2 greenhouse gas, methane is 20 to 30 times more potent than CO_2 over a century timescale. It accounted for 9% of all human-caused greenhouse gas emissions in the United States in 2011,[8] and its atmospheric concentration today is more than twice that of pre-industrial times.[24,25] Methane has an atmospheric lifetime of about 10 years before it is oxidized to CO_2, but it has about 25 times the global warming potential of CO_2. An increase in methane concentration in the industrial era has contributed to warming in many ways.[26]

Methane also has direct and indirect effects on climate because of its influences on atmospheric chemistry. Increases in atmospheric methane and VOCs are expected to deplete concentrations of hydroxyl radicals, causing methane to persist in the atmosphere and exert its warming effect for longer periods.[25,27] The hydroxyl radical is the most important "cleaning agent" of the troposphere (the active weather layer extending up to about 5 to 10 miles above the ground), where it is formed by a complex series of reactions involving ozone and ultraviolet light.[3]

Nitrogen and Phosphorus

The climate effects of an altered nitrogen cycle are substantial and complex.[4,28,29,30,31] Carbon dioxide, methane, and nitrous oxide contribute most of the human-caused increase in climate forcing, and the nitrogen cycle affects atmospheric concentrations of all three gases. Nitrogen cycling processes regulate ozone (O_3) concentrations in the troposphere and stratosphere, and produce atmospheric aerosols, all of which have additional direct effects on climate. Excess reactive nitrogen also has multiple indirect effects that simultaneously amplify and mitigate changes in climate. Changes in ozone and organic aerosols are short-lived, whereas changes in carbon dioxide and nitrous oxide have persistent impacts on the atmosphere.

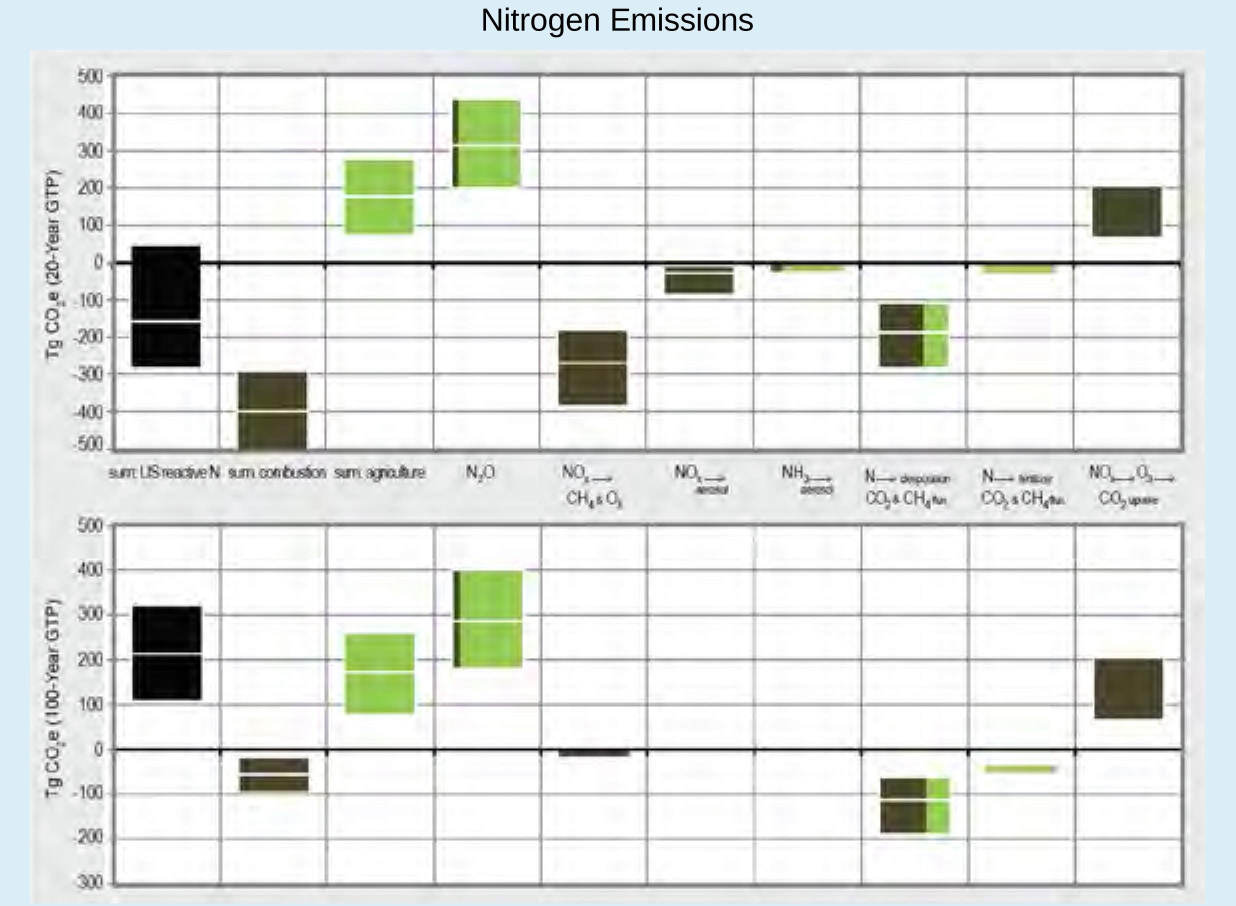

Figure 15.3. Figure shows how climate change will affect U.S. reactive nitrogen emissions, in Teragrams (Tg) CO_2 equivalent, on a 20-year (top) and 100-year (bottom) global temperature potential basis. Positive values on the vertical axis depict warming; negative values reflect cooling. The height of the bar denotes the range of uncertainty, and the white line denotes the best estimate. The relative contribution of combustion (dark brown) and agriculture (green) is denoted by the color shading. (Figure source: adapted from Pinder et al. 2012[28]).

The strongest direct effect of an altered nitrogen cycle is through emissions of nitrous oxide (N_2O), a long-lived and potent greenhouse gas that is increasing steadily in the atmosphere.[25,26] Globally, agriculture has accounted for most of the atmospheric rise in N_2O.[32,33] Roughly 60% of agricultural N_2O derives from elevated soil emissions resulting from the use of nitrogen fertilizer. Animal waste treatment accounts for about 30%, and the remaining 10% comes from crop-residue burning.[34] The U.S. reflects this global trend: around 75% to 80% of U.S. human-caused N_2O emissions are due to agricultural activities, with the majority being emissions from fertilized soil. The remaining 20% is derived from a variety of industrial and energy sectors.[35,36] While N_2O currently accounts for about 6% of human-caused warming,[26] its long lifetime in the atmosphere and rising concentrations will increase N_2O-based climate forcing over a 100-year time scale.[33,37,38]


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Excess reactive nitrogen indirectly exacerbates changes in climate by several mechanisms. Emissions of nitrogen oxides (NO_x) increase the production of tropospheric ozone, which is a greenhouse gas.[39] Elevated tropospheric ozone may reduce CO_2 uptake by plants and thereby reduce the terrestrial CO_2 sink.[40] Nitrogen deposition to ecosystems can also stimulate the release of nitrous oxide and methane and decrease methane uptake by soil microbes.[41]

However, excess reactive nitrogen also mitigates changes in greenhouse gas concentrations and climate through several intersecting pathways. Over short time scales, NO_x and ammonia emissions lead to the formation of atmospheric aerosols, which cool the climate by scattering or absorbing incoming radiation and by affecting cloud cover.[26,42] In addition, the presence of NO_x in the lower atmosphere increases the formation of sulfate and organic aerosols.[43] At longer time scales, NO_x can increase rates of methane oxidation, thereby reducing the lifetime of this important greenhouse gas.

One of the dominant effects of reactive nitrogen on climate stems from how it interacts with ecosystem carbon capture and storage, and thus, the carbon sink. As mentioned previously, addition of reactive nitrogen to natural ecosystems can increase carbon storage as long as other factors are not limiting plant growth, such as water and nutrient availability.[44] Nitrogen deposition from human sources is estimated to contribute to a global net carbon sink in land ecosystems of 917 to 1,830 million metric tons (1,010 to 2,020 million tons) of CO_2 per year. These are model-based estimates, as comprehensive, observationally-based estimates at large spatial scales are hindered by the limited number of field experiments. This net land sink represents two components: 1) an increase in vegetation growth as nitrogen limitation is alleviated by human-caused nitrogen deposition, and 2) a contribution from the influence of increased reactive nitrogen availability on decomposition. While the former generally increases with increased reactive nitrogen, the net effect on decomposition in soils is not clear. The net effect on total ecosystem carbon storage was an average of 37 metric tons (41 tons) of carbon stored per metric ton of nitrogen added in forests in the U.S. and Europe.[45]

When all direct and indirect links between reactive nitrogen and climate in the U.S. are added up, a recent estimate suggests a modest reduction in the rate of warming in the near term (next several decades), but a progressive switch to greater net warming over a 100-year timescale.[28,29] That switch is due to a reduction in nitrogen oxide (NO_x) emissions, which provide modest cooling effects, a reduction in the nitrogen-stimulated CO_2 storage in forests, and a rising importance of agricultural nitrous oxide emissions. Current policies tend to reinforce this switch. For example, policies that reduce nitrogen oxide and sulfur oxide emissions have large public health benefits, but also reduce the indirect climate mitigation co-benefits by reducing carbon storage and aerosol formation.

Changes in the phosphorus cycle have no direct effects on climate, but phosphorus availability constrains plant and microbial activity in a wide variety of land- and water-based ecosystems.[46,47] Changes in phosphorus availability due to human activity can therefore have indirect impacts on climate and the emissions of greenhouse gases in a variety of ways. For example, in land-based ecosystems, phosphorus availability can limit both CO_2 storage and decomposition[46,48] as well as the rate of nitrogen accumulation.[49] In turn, higher nitrogen inputs can alter phosphorus cycling via changes in the production and activity of enzymes that release phosphorus from decaying organic matter,[50] creating another mechanism by which rising nitrogen inputs can stimulate carbon uptake.

Other Effects: Sulfate Aerosols

In addition to the aerosol effects from nitrogen mentioned above, there are both direct and indirect effects on climate from other aerosol sources. Components of the sulfur cycle exert a cooling effect through the formation of sulfate aerosols created from the oxidation of sulfur dioxide (SO_2) emissions.[26] In the United States, the dominant source of sulfur dioxide is coal combustion. Sulfur dioxide emissions rose until 1980, but have since decreased by more than 50% following a series of air-quality regulations and incentives focused on improving human health and the environment, as well as reductions in the delivered price of low-sulfur coal.[51] That decrease in emissions has had a marked effect on U.S. climate forcing: between 1970 and 1990, sulfate aerosols caused cooling, primarily over the eastern U.S., but since 1990, further reductions in sulfur dioxide emissions have reduced the cooling effect of sulfate aerosols by half or more.[42] Continued declines in sulfate aerosol cooling are projected for the future,[42] particularly if coal continues to be replaced by natural gas (which contains far fewer sulfur impurities) for electricity generation. Here, as with nitrogen oxide emissions, the environmental and socioeconomic tradeoffs are important to recognize: lower sulfur dioxide and nitrogen oxide emissions remove some climate cooling agents, but improve ecosystem health and save lives.[16,31,52]

Three low-concentration industrial gases are particularly potent for trapping heat: nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and trifluoromethyl sulfur pentafluoride (SF_5CF_3). None currently makes a major contribution to climate forcing, but since their emissions are increasing and their effects last for millennia, continued monitoring is important.

Key Message 3: Impacts and Options

Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.

Climate change alters key aspects of biogeochemical cycling, creating the potential for feedbacks that alter both warming and cooling processes into the future. For example, as soils warm, the rate of decomposition will increase, adding more CO_2 to the atmosphere. In addition, both climate and biogeochemistry interact strongly with environmental and ecological concerns, such as biodiversity loss, freshwater and marine eutrophication (unintended fertilization of aquatic ecosystems that leads to water quality problems), air pollution, human health, food security, and water resources. Many of the latter connections are addressed in other sections of this assessment, but we summarize some of them here because consideration of mitigation and adaptation options for changes in climate and biogeochemistry often requires this broader context.

Climate-Biogeochemistry Feedbacks

Both rising temperatures and changes in water availability can alter climate-relevant biogeochemical processes. For example, as summarized above, nitrogen deposition drives temperate forest carbon storage, both by increasing plant growth and by slowing organic-matter decomposition.[53] Higher temperatures will counteract soil carbon storage by increasing decomposition rates and subsequent emission of CO_2 via microbial respiration. However, that same increase in decomposition accelerates the release of reactive nitrogen (and phosphorus) from organic matter, which in turn can fuel additional plant growth.[44] Temperature also has direct effects on net primary productivity (the total amount of CO_2 stored by a plant through photosynthesis minus the amount released through respiration). The combined effects on ecosystem carbon storage will depend on the extent to which nutrients constrain both net primary productivity and decomposition, on the extent of warming, and on whether any simultaneous changes in water availability occur.[54]

Similarly, natural methane sources are sensitive to variations in climate; ice core records show a strong correlation between methane concentrations and warmer, wetter conditions.[55] Thawing permafrost in polar regions is of particular concern because it stores large amounts of methane that could potentially be released to the atmosphere.

Biogeochemistry, Climate, and Interactions with Other Factors

Societal options for addressing links between climate and biogeochemical cycles must often be informed by connections to a broader context of global environmental changes. For example, both climate change and nitrogen deposition can reduce biodiversity in water- and land-based ecosystems. The greatest combined risks are expected to occur where critical loads are exceeded.[56,57] A critical load is defined as the input rate of a pollutant below which no detrimental ecological effects occur over the long-term according to present knowledge.[57] Although biodiversity is often shown to decline when nitrogen deposition is high due to fossil fuel combustion and agricultural emissions,[57,58] the compounding effects of multiple stressors are difficult to predict. Warming and changes in water availability have been shown to interact with nitrogen in additive or synergistic ways to exacerbate biodiversity loss.[59] Unfortunately, very few multi-factorial studies have been done to address this gap.

Human induced acceleration of the nitrogen and phosphorus cycles already causes widespread freshwater and marine eutrophication,[60,61] a problem that is expected to worsen under a warming climate.[61,62] Without efforts to reduce future climate change and to slow the acceleration of biogeochemical cycles, existing climate changes will combine with increasing inputs of nitrogen and phosphorus into freshwater and estuarine ecosystems. This combination of changes is projected to have substantial negative effects on water quality, human health, inland and coastal fisheries, and greenhouse gas emissions.[18,61]

Similar concerns – and opportunities for the simultaneous reduction of multiple environmental problems (known as "co-benefits") – exist in the realms of air pollution, human health, and food security. For example, methane, volatile organic compounds, and nitrogen oxide emissions all contribute to the formation of tropospheric ozone, which is a greenhouse gas and has negative consequences for human health and crop and forest productivity.[37,63,64] Rates of ozone formation are accelerated by higher temperatures, creating a reinforcing cycle between rising temperatures and continued human alteration of the nitrogen and carbon cycles.[65] Rising temperatures also work against some of the benefits of air pollution control.[64] Some changes will trade gains in one arena for declines in others. For example, lowered NO_x, NH_x, and SO_x emissions remove cooling agents from the atmosphere, but improve air quality.[16,31] Recent analyses suggest that targeting reductions in compounds like methane and black carbon aerosols that have both climate and air-pollution consequences can achieve significant improvements in not only the rate of climate change, but also in human health.[31] Finally, reductions in excess nitrogen and phosphorus from agricultural and industrial activities can potentially reduce the rate and impacts of climate change, while simultaneously addressing concerns in biodiversity, water quality, food security, and human health.[66]

Many Factors Combine to Affect Biogeochemical Cycles

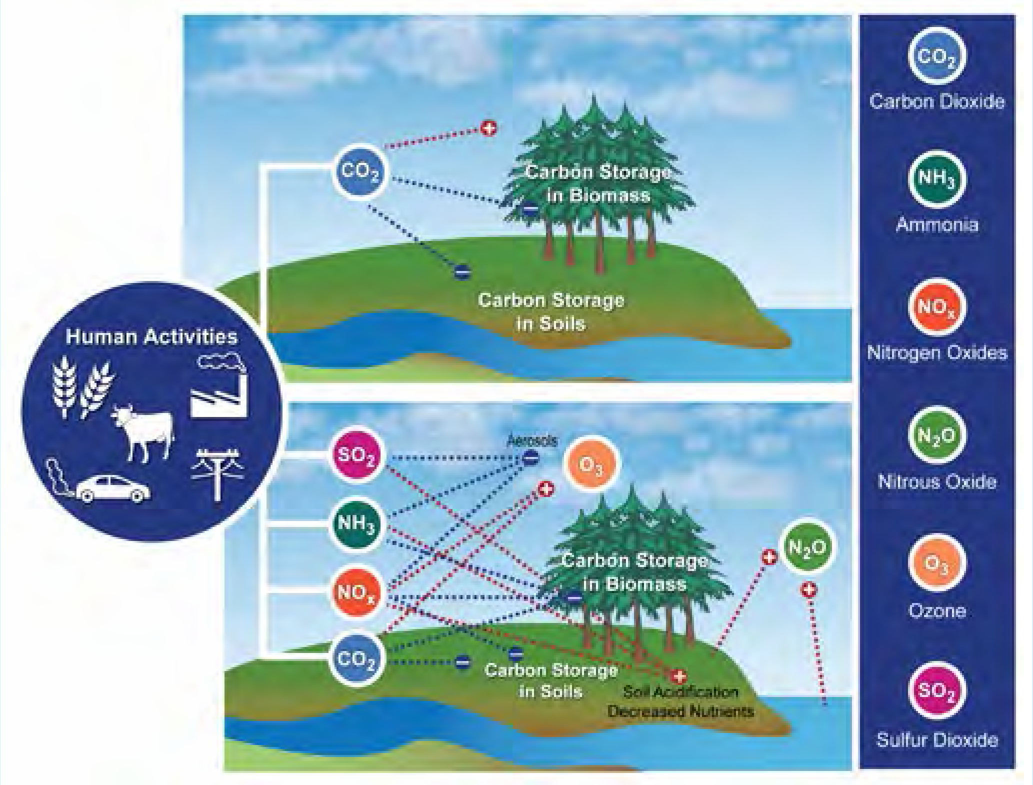

Figure 15.4. Top panel shows the impact of the alteration of the carbon cycle alone on radiative forcing. The bottom panel shows the impacts of the alteration of carbon, nitrogen, and sulfur cycles on radiative forcing. SO_2 and NH_3 increase aerosols and decrease radiative forcing. NH_3 is likely to increase plant biomass, and consequently decrease forcing. NO_x is likely to increase the formation of tropospheric ozone (O_3) and increase radiative forcing. Ozone has a negative effect on plant growth/biomass, which might increase radiative forcing. CO_2 and NH_3 act synergistically to increase plant growth, and therefore decrease radiative forcing. SO_2 is likely to reduce plant growth, perhaps through the leaching of soil nutrients, and consequently increase radiative forcing. NO_x is likely to reduce plant growth directly and through the leaching of soil nutrients, therefore increasing radiative forcing. However, it could act as a fertilizer that would have the opposite effect.

ESTIMATING THE U.S. CARBON SINK

Any natural or engineered process that temporarily or permanently removes and stores carbon dioxide (CO_2) from the atmosphere is considered a carbon "sink." Temporary (10 to 100 years) CO_2 sinks at the global scale include absorption by plants as they photosynthesize, as well as CO_2 dissolution into the ocean. Forest biomass and soils in North America offer large temporary carbon sinks in the global carbon budget; however, the spatial distribution, longevity, and mechanisms controlling these sinks are less certain.[67] Understanding these processes is critical for predicting how ecosystem carbon sinks will change in the future, and potentially for managing the carbon sink as a mitigation strategy for climate change.

Table 15.1. Carbon (C) sinks and uncertainty estimated by Pacala et al. for the first State of the Carbon Cycle Report.[23] Forests take up the highest percentage of carbon of all land-based carbon sinks. Due to a number of factors, there are high degrees of uncertainty in carbon sink estimates.

Land Area	C sink (Tg C/y) (95% CI)	Method
Forest	-256 (+/- 50%)	inventory, modeled
Wood products	-57 (+/- 50%)	inventory
Woody encroachment	-120 (+/- >100%)	inventory
Agricultural soils	-8 (+/- 50%)	modeled
Wetlands	-23 (+/- >100%)	inventory
Rivers and reservoirs	-25 (+/- 100%)	inventory
Net Land Sink	**-489 (+/- 50%)**	**inventory**

Both inventory (measurement) and modeling techniques have been used to estimate land-based carbon sinks at a range of scales in both time and space. For inventory methods, carbon stocks are measured at a location at two points in time, and the amount of carbon stored or lost can be estimated over the intervening time period. This method is widely used to estimate the amount of carbon stored in forests in the United States over timescales of years to decades. Terrestrial biosphere models estimate carbon sinks by modeling a suite of processes that control carbon cycling dynamics, such as photosynthesis (CO_2 uptake by plants) and respiration (CO_2 release by plants, animals, and microorganisms in soil and water). Field-based data and/or remotely sensed data are used as inputs and also to validate these models. Estimates of the land-based carbon sink can vary depending on the data inputs and how different processes are modeled.[22] Atmospheric inverse models use information about atmospheric CO_2 concentrations and atmospheric transport (like air currents) to estimate the terrestrial carbon sink.[68] This approach can provide detailed information about carbon sinks over time. However, because atmospheric CO_2 is well-mixed and monitoring sites are widely dispersed, these models estimate fluxes over large areas and it is difficult to identify processes responsible for the sink from these data.[22] Recent estimates using atmospheric inverse models show that global land and ocean carbon sinks are stable or even increasing globally.[69]

U.S. Carbon Sinks Absorb a Fraction of CO_2 Emissions

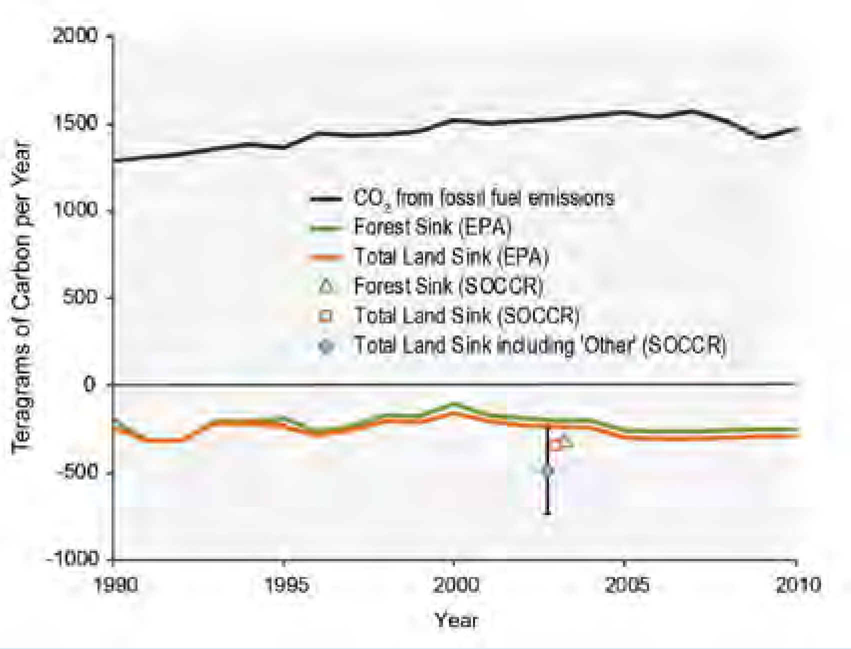

Figure 15.5. Figure shows growth in fossil fuel CO_2 emissions (black line) and forest and total land carbon sinks in the U.S. for 1990–2010 (green and orange lines; from EPA 2012[21]) and for 2003 (symbols; from the first State of the Carbon Cycle Report[67]). Carbon emissions are significantly higher than the total land sink's capacity to absorb and store them. (Data from EPA 2012 and CCSP 2007[21,67]).

Continued

ESTIMATING THE U.S. CARBON SINK (CONTINUED)

U.S. Carbon Sources and Sinks from 1991 to 2000 and 2001 to 2010

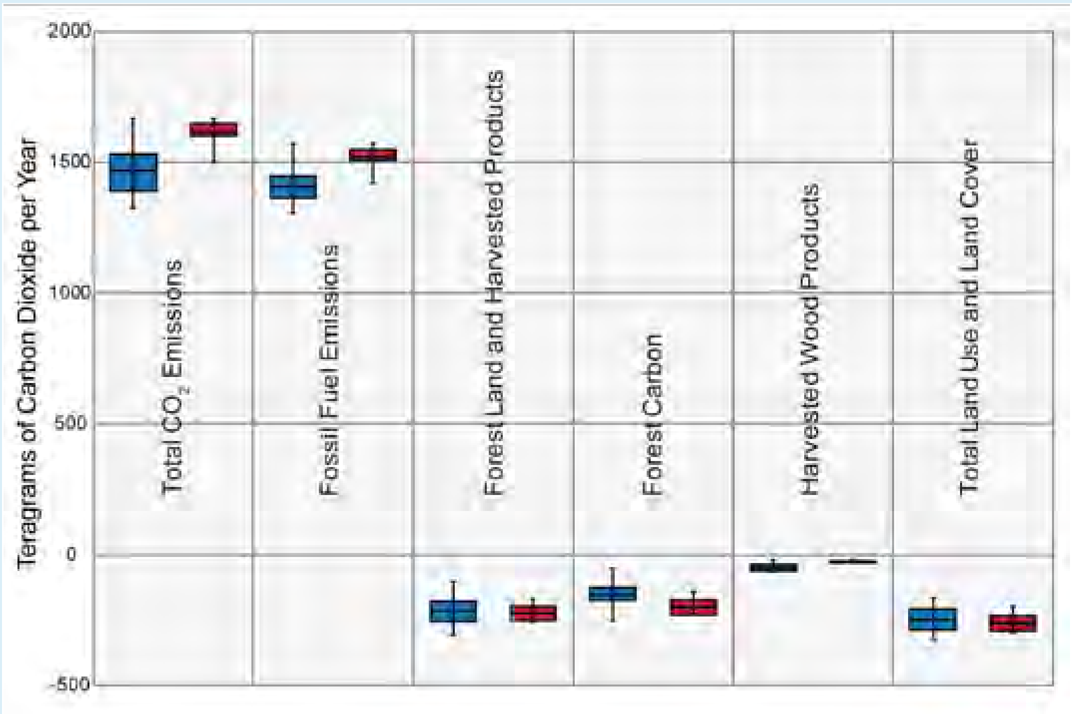

Figure 15.6. Changes in CO_2 emissions and land-based sinks in two recent decades, showing among-year variation (vertical lines: minimum and maximum estimates among years; boxes: 25th and 75th quartiles; horizontal line: median). Total CO_2 emissions, as well as total CO_2 emissions from fossil fuels, have risen; land-based carbon sinks have increased slightly, but at a much slower pace. (Data from EPA 2012 and CCSP 2007[21,67]).

The U.S. Environmental Protection Agency (EPA) conducts an annual inventory of U.S. greenhouse gas emissions and sinks as part of the nation's commitments under the Framework Convention on Climate Change. Estimates are based on inventory studies and models validated with field-based data (such as the CENTURY model) in accordance with the Intergovernmental Panel on Climate Change (IPCC) best practices.[70] An additional comprehensive assessment, The First State of the Carbon Cycle Report (SOCCR), provides estimates for carbon sources and sinks in the U.S. and North America around 2003.[67] This assessment also utilized inventory and field-based terrestrial biosphere models, and incorporated additional land sinks not explicitly included in EPA assessments.

Data from these assessments suggest that the U.S. carbon sink has been variable over the last two decades, but still absorbs and stores a small fraction of CO_2 emissions. The forest sink comprises the largest fraction of the total land sink in the United States, annually absorbing 7% to 24% (with a best estimate of 16%) of fossil fuel CO_2 emissions during the last two decades. Because the U.S. Forest Service has conducted detailed forest carbon inventory studies, the uncertainty surrounding the estimate for the forest sink is lower than for most other components (see Pacala et al. 2007, Table 2[23]). The role of lakes, reservoirs, and rivers in the carbon budget, in particular, has been difficult to quantify and is rarely included in national budgets.[71] The IPCC guidelines for estimating greenhouse gas sources or sinks from lakes, reservoirs, or rivers are included in the "wetlands" category, but only for lands converted to wetlands. These ecosystems are not included in the EPA's estimates of the total land sink. Rivers and reservoirs were estimated to be a sink in the State of the Carbon Cycle analysis,[23] but recent studies suggest that inland waters may actually be an important source of CO_2 to the atmosphere.[72] It is important to note that these two methods use different datasets, different models, and different methodologies to estimate land-based carbon sinks in the United States. In particular, we note that the EPA Inventory, consistent with IPCC Guidelines for national inventories, includes only carbon sinks designated as human-caused, while the SOCCR analysis does not make this distinction.

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15: BIOGEOCHEMICAL CYCLES

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages and supporting text summarize extensive evidence documented in two technical input reports submitted to the NCA: 1) a foundational report supported by the Departments of Energy and Agriculture: *Biogeochemical Cycles and Biogenic Greenhouse Gases from North American Terrestrial Ecosystems: A Technical Input Report for the National Climate Assessment,*[30] and 2) an external report: *The Role of Nitrogen in Climate Change and the Impacts of Nitrogen-Climate Interactions on Terrestrial and Aquatic Ecosystems, Agriculture, and Human Health in the United States: A Technical Report Submitted to the U.S. National Climate Assessment.*[4] The latter report was supported by the International Nitrogen Initiative, a National Science Foundation grant, and the David and Lucille Packard Foundation.

Author meetings and workshops were held regularly for the foundational report,[30] including a workshop at the 2011 Soil Science Society of America meeting. A workshop held in July 2011 at the USGS John Wesley Powell Center for Analysis and Synthesis in Fort Collins, CO, focused on climate-nitrogen actions and was summarized in the second primary source.[4] An additional 15 technical input reports on various topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The entire author team for this chapter conducted its deliberations by teleconference from April to June 2012, with three major meetings resulting in an outline and a set of key messages. The team came to expert consensus on all of the key messages based on their reading of the technical inputs, other published literature, and professional judgment. Several original key messages were later combined into a broader set of statements while retaining most of the original content of the chapter. Major revisions to the key messages, chapter, and traceable accounts were approved by authors; further minor revisions were consistent with the messages intended by the authors.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,31] In particular, one report[4] focused on changes in the nitrogen cycle and was comprehensive. Original literature was consulted for changes in other biogeochemical cycles. The foundational report[30] updated several aspects of our understanding of the carbon balance in the United States.

Publications have shown that human activities have altered biogeochemical cycles. A seminal paper comparing increases in the global fluxes of carbon (C), nitrogen (N), sulfur (S), and phosphorous (P) was published in 2000[73] and was recently updated.[3] Changes observed in the nitrogen cycle[1,17,18] show anthropogenic sources to be far greater than natural ones.[14,36,47] For phosphorus, the effect of added phosphorus on plants and microbes is well understood.[19,46,47] Extensive research shows that increases in CO_2 are the strongest human impact forcing climate change, mainly because the concentration of CO_2 is so much greater than that of other greenhouse gases.[5,7,73]

New information and remaining uncertainties

The sources of C, N, and P are from well-documented processes, such as fossil fuel burning and fertilizer production and application. The flux from some processes is well known, while others have significant remaining uncertainties.

Some new work has synthesized the assessment of global and national CO_2 emissions[7] and categorized the major CO_2 sources and sinks.[4,30] Annual updates of CO_2 emissions and sink inventories are done by EPA (for example, EPA 2013[8]).

Advances in the knowledge of the nitrogen cycle have quantified that human-caused reactive nitrogen inputs are now at least five times greater than natural inputs.[4,13,14]

Assessment of confidence based on evidence

High confidence. Evidence for human inputs of C, N, and P come from academic, government, and industry sources. The data show substantial agreement.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

The likelihood of continued dominance of CO_2 over other greenhouse gases as a driver of global climate change is also judged to be **high**, because its concentration is an order of magnitude higher and its rate of change is well known.

Key message #2 Traceable Account

In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO2 and other greenhouse gases.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,30] The "Estimating the U.S. Carbon Sink" section relies on multiple sources of data that are described therein.

Numerous studies of the North American and U.S. carbon sink have been published in reports and the scientific literature. Estimates of the percentage of fossil fuel CO_2 emissions that are captured by forest, cropland, and other lands vary from a low of 7% to a high of about 24%, when the carbon storage is estimated from carbon inventories.[7,22,36] The forest sink has persisted in the U.S. as forests that were previously cut have regrown. Further studies show that carbon uptake can be increased to some extent by a fertilization effect with reactive nitrogen[44,45] and phosphorus,[46,47,48] both nutrients that can limit the rate of photosynthesis. The carbon sink due to nitrogen fertilization is projected to lessen in the future as controls on nitrogen emissions come into play.[28]

While carbon uptake by ecosystems has a net cooling effect, trace gases emitted by ecosystems have a warming effect that can offset the cooling effect of the carbon sink.[26] The most important of these gases are methane and nitrous oxide (N_2O), the concentrations of which are projected to rise.[25,26,33,37,38]

New information and remaining uncertainties

The carbon sink estimates have very wide margins of error. The percent of U.S. CO_2 emissions that are stored in ecosystems depends on which years are used for emissions and whether inventories, ecosystem process models, atmospheric inverse models, or some combination of these techniques are used to estimate the sink size (see "Estimating the U.S. Carbon Sink"). The inventories are continually updated (for example, EPA 2013[8]), but there is a lack of congruence on which of the three techniques is most reliable. A recent paper that uses atmospheric inverse modeling suggests that the global land and ocean carbon sinks are stable or increasing.[69]

While known to be significant, continental-scale fluxes and sources of the greenhouse gases N_2O and CH_4 are based on limited data and are potentially subject to revision. Recent syntheses[28] evaluate the dynamics of these two important gases and project future changes. Uncertainties remain high.

Assessment of confidence based on evidence

We have **very high** confidence that the value of the forest carbon sink lies within the range given, 7% to 24% (with a best estimate of 16%) of annual U.S. greenhouse gas emissions. There is wide acceptance that forests and soils store carbon in North America, and that they will continue to do so into the near future. The exact value of the sink strength is very poorly constrained, however, and knowledge of the projected future sink is low. As forests age, their capacity to store carbon in living biomass will necessarily decrease,[10] but if other, unknown sinks are dominant, ecosystems may continue to be a carbon sink.

We have **high** confidence that the combination of ecosystem carbon storage of human-caused greenhouse gas emissions and potential warming from other trace gases emitted by ecosystems will ultimately result in a net warming effect. This is based primarily on one recent synthesis,[28] which provides ranges for multiple factors and describes the effects of propagating uncertainties. However, the exact amount of warming or cooling produced by various gases is not yet well known, because of the interactions of multiple factors.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,30]

The climate–biogeochemical cycle link has been demonstrated through numerous studies on the effects of reactive nitrogen and phosphorus on forest carbon uptake and storage, and decomposition of organic matter;[44,53] temperature effects on ecosystem productivity;[54] and sensitivity of natural methane emissions to climate variation.[55]

Where the nitrogen and phosphorus cycles are concerned, a number of publications have reported effects of excess loading on ecosystem processes[60,61] and have projected these effects to worsen.[61,62] Additionally, studies have reported the potential for future climate change and increasing nitrogen and phosphorus loadings to have an additive effect and the need for remediation.[18,61] The literature suggests that co-benefits are possible from addressing the environmental concerns of both nutrient loading and climate change.[4,31,64,65,66]

New information and remaining uncertainties

Scientists are still investigating the impact of nitrogen deposition on carbon uptake and of sulfur and nitrogen aerosols on radiative forcing.

Recent work has shown that more than just climate change aspects can benefit from addressing multiple environmental concerns (air/water quality, biodiversity, food security, human health, and so on)

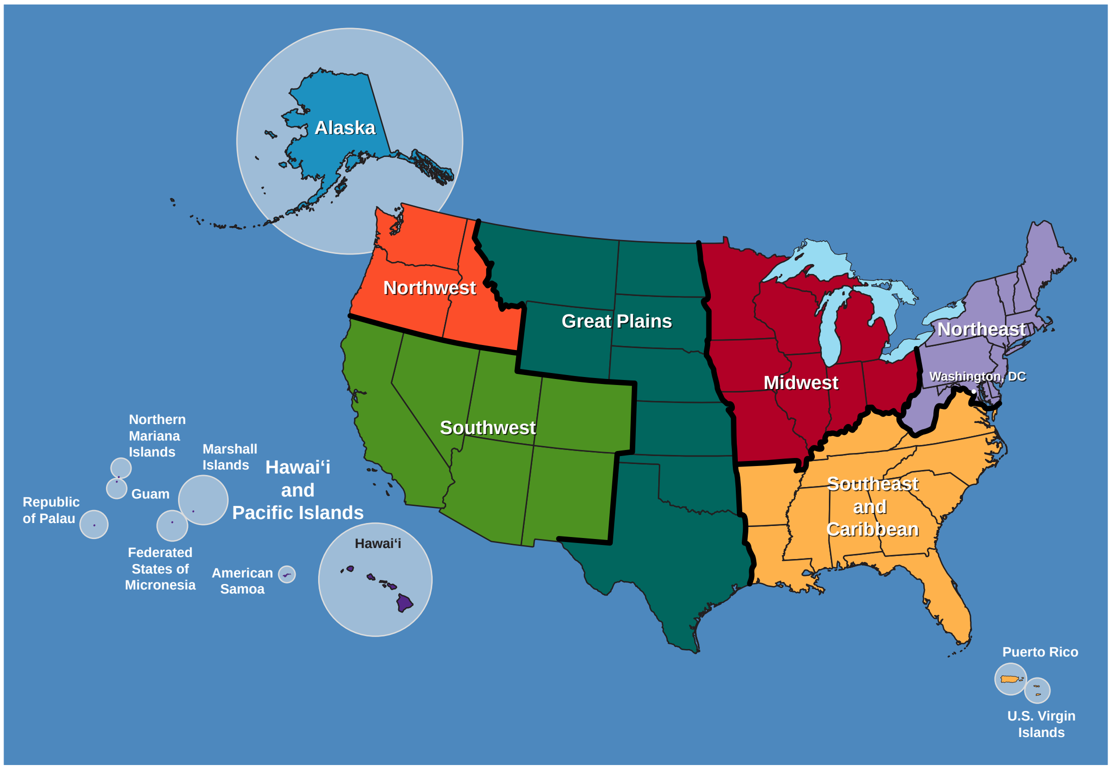
Assessment of confidence based on evidence

High. We have a **high** degree of confidence that climate change will affect biogeochemical cycles through its effects on ecosystem structure and function (species composition and productivity). Similarly, there is **high** confidence that altered biogeochemical cycles will affect climate change, as for example in the increased rates of carbon storage in forests and soils that often accompany excess nitrogen deposition**.**

REGIONS

From the Rocky Mountains to the Shenandoah Valley, the Great Lakes to the Gulf of Mexico, our country's landscapes and communities vary dramatically. But amidst our geographical and economic diversity, we share many common attributes and challenges. One common challenge facing every U.S. region is a new and dynamic set of realities resulting from our changing climate.

The evidence can be found in every region, and impacts are visible in every state. Some of the most dramatic changes are in Alaska, where average temperatures have increased more than twice as fast as the rest of the country. The rapid decline of Arctic sea ice cover in the last decade is reshaping that region. In the Southwest, a combination of increased temperatures and reductions in annual precipitation are already affecting forests and diminishing water supplies. Meanwhile, that region's population continues to grow at double-digit rates, increasing the stress on water supplies. In various regions, evidence of climate change is apparent in ecosystem changes, such as species moving northward, increases in invasive species and insect outbreaks, and changes in the length of the growing season. In many cities, impacts to the urban environment are closely linked to the changing climate, with increased flooding, greater incidence of heat waves, and diminished air quality. Along most of our coastlines, increasing sea levels and associated threats to coastal areas and infrastructure are becoming a common experience.



For all U.S. regions, warming in the future is projected to be very large compared to historical variations. Precipitation patterns will be altered as well, with some regions becoming drier and some wetter. The exact location of some of these future changes is not easy to pinpoint, because the continental U.S. straddles a transition zone between projected drier conditions in the sub-tropics (south) and wetter conditions at higher latitudes (north). As a result, projected precipitation changes in the northernmost states (which will get wetter) and southernmost states (which will get drier) are more certain than those for the central areas of the country. The heaviest precipitation events are projected to increase everywhere, and by large amounts. Extended dry spells are also projected to increase in length.

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Regional differences in climate change impacts provide opportunities as well as challenges. A changing climate requires alterations in historical agricultural practices, which, if properly anticipated, can have some benefits. Warmer winters mean reductions in heating costs for those in the northern portions of the country. Well-designed adaptation and mitigation actions that take advantage of regional conditions can significantly enhance the nation's resilience in the face of multiple challenges, which include many factors in addition to climate change.

The regions defined in this report intentionally follow state lines (see Figure 1 and Table 1), but landscape features such as forests and mountain ranges do not follow these artificial boundaries. The array of distinct landscapes within each region required difficult choices of emphasis for the authors. The chapters that follow provide a summary of changes and impacts that are observed and anticipated in each of the eight regions of the United States, as well as on oceans and coasts.

For more information about the regional climate histories and projections[1] and sea level rise scenarios[2] developed for the National Climate Assessment, and used throughout this report, see Ch. 2: Our Changing Climate and Appendix 5: Scenarios and Model

Table 1: Composition of NCA Regions

Region	Composition
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia, District of Columbia,
Southeast and Caribbean	Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, Puerto Rico, U.S. Virgin Islands
Midwest	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
Great Plains	Kansas, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, Wyoming
Northwest	Idaho, Oregon, Washington
Southwest	Arizona, California, Colorado, Nevada, New Mexico, Utah
Alaska	Alaska
Hawai'i and U.S. Pacific Islands	Hawai'i, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Republic of the Marshall Islands, Republic of Palau, Territory of American Samoa, Territory of Guam

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Climate Change Impacts in the United States

CHAPTER 16
NORTHEAST

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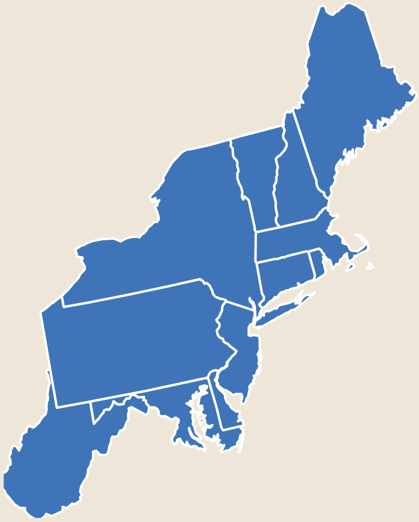

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On the Web: http://nca2014.globalchange.gov/report/regions/northeast

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

16 NORTHEAST

KEY MESSAGES

1. **Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.**
2. **Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.**
3. **Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.**
4. **While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.**

Sixty-four million people are concentrated in the Northeast. The high-density urban coastal corridor from Washington, D.C., north to Boston is one of the most developed environments in the world. It contains a massive, complex, and long-standing network of supporting infrastructure. The region is home to one of the world's leading financial centers, the nation's capital, and many defining cultural and historical landmarks.

The region has a vital rural component as well. The Northeast includes large expanses of sparsely populated but ecologically and agriculturally important areas. Much of the Northeast landscape is dominated by forest, but the region also has grasslands, coastal zones, beaches and dunes, and wetlands, and it is known for its rich marine and freshwater fisheries. These natural areas are essential to recreation and tourism sectors and support jobs through the sale of timber, maple syrup, and seafood. They also contribute important ecosystem services to broader populations – protecting water supplies, buffering shorelines, and sequestering carbon in soils and vegetation. The twelve Northeastern states have more than 180,000 farms, with $17 billion in annual sales.[1] The region's ecosystems and agricultural systems are tightly interwoven, and both are vulnerable to a changing climate.

Although urban and rural regions in the Northeast have profoundly different built and natural environments, both include populations that have been shown to be highly vulnerable to climate hazards and other stresses. Both also depend on aging infrastructure that has already been stressed by climate hazards including heat waves, as well as coastal and riverine flooding due to a combination of sea level rise, storm surge, and extreme precipitation events.

The Northeast is characterized by a diverse climate.[2] Average temperatures in the Northeast generally decrease to the north, with distance from the coast, and at higher elevations. Average annual precipitation varies by about 20 inches throughout the Northeast with the highest amounts observed in coastal and select mountainous regions. During winter, frequent storms bring bitter cold and frozen precipitation, especially to the north. Summers are warm and humid, especially to the south. The Northeast is often affected by extreme events such as ice storms, floods, droughts, heat waves, hurricanes, and major storms in the Atlantic Ocean off the northeast coast, referred to as nor'easters. However, variability is large in both space and

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time. For example, parts of southern New England that experienced heavy snows in the cold season of 2010-2011 experienced little snow during the cold season of 2011-2012. Of course, even a season with low totals can feature costly extreme events; snowfall during a 2011 pre-Halloween storm that hit most of the Northeast, when many trees were still in leaf, knocked out power for up to 10 days for thousands of households.


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Observed Climate Change

Between 1895 and 2011, temperatures in the Northeast increased by almost 2˚F (0.16˚F per decade), and precipitation increased by approximately five inches, or more than 10% (0.4 inches per decade).[3] Coastal flooding has increased due to a rise in sea level of approximately 1 foot since 1900. This rate of sea level rise exceeds the global average of approximately 8 inches (see Ch. 2: Our Changing Climate, Key Message 10; Ch. 25: Coasts), due primarily to land subsidence,[4] although recent research suggests that changes in ocean circulation in the North Atlantic – specifically, a weakening of the Gulf Stream – may also play a role.[5]

The Northeast has experienced a greater recent increase in extreme precipitation than any other region in the United States; between 1958 and 2010, the Northeast saw more than a 70% increase in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) (see Ch. 2: Our Changing Climate, Figure 2.18).[7]

Sea Level is Rising

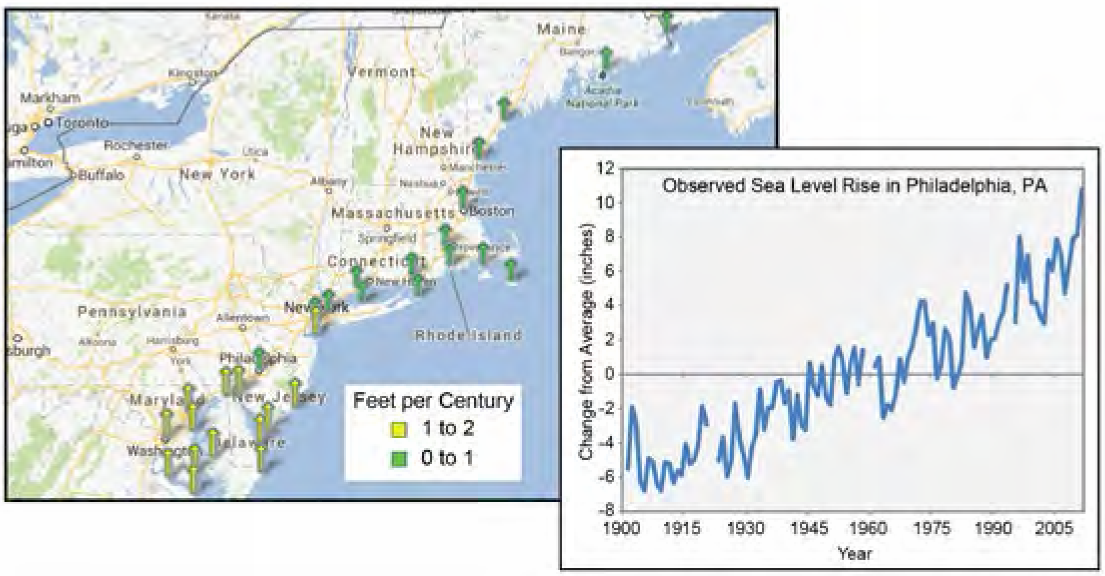

Figure 16.1. (Map) Local sea level trends in the Northeast region. Length of time series for each arrow varies by tide gauge location. (Figure source: NOAA[6]). (Graph) Observed sea level rise in Philadelphia, PA, has significantly exceeded the global average of 8 inches over the past century, increasing the risk of impacts to critical urban infrastructure in low-lying areas. Over 100 years (1901-2012), sea level increased 1.2 feet (Data from Permanent Service for Mean Sea Level).

Projected Climate Change

As in other areas, the amount of warming in the Northeast will be highly dependent on global emissions of heat-trapping gases. If emissions continue to increase (as in the A2 scenario), warming of 4.5F° to 10°F is projected by the 2080s; if global emissions were reduced substantially (as in the B1 scenario), projected warming ranges from about 3°F to 6°F by the 2080s.[3]

Under both emissions scenarios, the frequency, intensity, and duration of heat waves is expected to increase, with larger increases under higher emissions (Ch. 2: Our Changing Climate). Much of the southern portion of the region, including the majority of Maryland and Delaware, and southwestern West Virginia and New Jersey, are projected by mid-century to experience more than 60 additional days per year above 90°F compared to the end of last century under continued increases in emissions (Figure 16.2, A2 scenario). This will affect the region's vulnerable populations, infrastructure, agriculture, and ecosystems.

Projected Increases in the Number of Days over 90°F

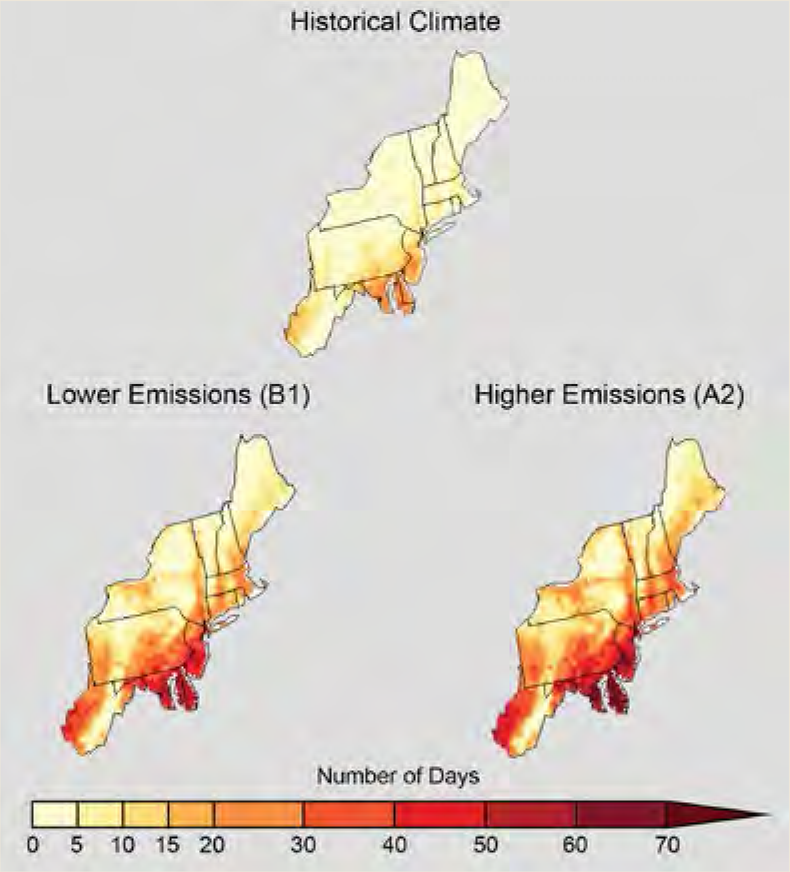

Figure 16.2. Projected increase in the number of days per year with a maximum temperature greater than 90°F averaged between 2041 and 2070, compared to 1971-2000, assuming continued increases in global emissions (A2) and substantial reductions in future emissions (B1). (Figure source: NOAA NCDC / CICS-NC).

The frequency, intensity, and duration of cold air outbreaks is expected to decrease as the century progresses, although some research suggests that loss of Arctic sea ice could indirectly reduce this trend by modifying the jet stream and mid-latitude weather patterns.[8,9]

Projections of precipitation changes are less certain than projections of temperature increases.[3] Winter and spring precipitation is projected to increase, especially but not exclusively in the northern part of the region (Ch. 2: Our Changing Climate, Key Messages 5 and 6).[3,10] A range of model projections for the end of this century under a higher emissions scenario (A2), averaged over the region, suggests about 5% to 20% (25th to 75th percentile of model projections) increases in winter precipitation. Projected changes in summer and fall, and for the entire year, are generally small at the end of the century compared to natural variations (Ch. 2: Our Changing Climate, Key Message 5).[3] The frequency of heavy downpours is projected to continue to increase as the century progresses (Ch. 2: Our Changing Climate, Key Message 6). Seasonal drought risk is also projected to increase in summer and fall as higher temperatures lead to greater evaporation and earlier winter and spring snowmelt.[11]

Global sea levels are projected to rise 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 10),[12] depending in large part on the extent to which the Greenland and West Antarctic Ice Sheets experience significant melting. Sea level rise along most of the coastal Northeast is expected to exceed the global average rise due to local land subsidence, with the possibility of even greater regional sea level rise if the Gulf Stream weakens as some models suggest.[5,13] Sea level rise of two feet, without any changes in storms, would more than triple the frequency of dangerous coastal flooding throughout most of the Northeast.[14]

Although individual hurricanes cannot be directly attributed to climate change, Hurricanes Irene and Sandy nevertheless provided "teachable moments" by demonstrating the region's vulnerability to extreme weather events and the potential for adaptation to reduce impacts.

HURRICANE VULNERABILITY

Two recent events contrast existing vulnerability to extreme events: Hurricane Irene, which produced a broad swath of very heavy rain (greater than five inches in total and sometimes two to three inches per hour in some locations) from southern Maryland to northern Vermont from August 27 to 29, 2011; and Hurricane Sandy, which caused massive coastal damage from storm surge and flooding along the Northeast coast from October 28 to 30, 2012.

Rainfall associated with Irene led to hydrological extremes in the region. These heavy rains were part of a broader pattern of wet weather preceding the storm (rainfall totals for August and September exceeded 25 inches across much of the Northeast) that left the region predisposed to extreme flooding from Irene; for example, the Schoharie Creek in New York experienced a 500-year flood.[15]

Flooding and Hurricane Irene

Figure 16.3. Hurricane Irene over the Northeast on August 28, 2011. The storm, which brought catastrophic flooding rains to parts of the Northeast, took 41 lives in the United States, and the economic cost was estimated at $16 billion.[16] (Figure source: MODIS instrument on NASA's Aqua satellite).

In anticipation of Irene, the New York City mass transit system was shut down, and 2.3 million coastal residents in Delaware, New Jersey, and New York faced mandatory evacuations. However, it was the inland impacts, especially in upstate New York and in central and southern Vermont, that were most severe. Ironically, many New York City residents fled to inland locations, which were harder hit. Flash flooding washed out roads and bridges, undermined railroads, brought down trees and power lines, flooded homes and businesses, and damaged floodplain forests. In Vermont, more than 500 miles of roadways and approximately 200 bridges were damaged, with estimated rebuilding costs of $175 to $250 million. Hazardous wastes were released in a number of areas, and 17 municipal wastewater treatment plants were breached by floodwaters. Agricultural losses included damage to barn structures and flooded fields of crops. Many towns and villages were isolated for days due to infrastructure impacts from river flooding (see also Ch. 5: Transportation, "Tropical Storm Irene Devastates Vermont Transportation in August 2011").[2] Affected residents suffered from increased allergen exposure due to mold growth in flooded homes and other structures and were exposed to potentially harmful chemicals and pathogens in their drinking water. In the state of Vermont, cleaning up spills from aboveground hazardous waste tanks cost an estimated $1.75 million. Septic systems were also damaged from high groundwater levels and river or stream erosion, including 17 septic system failures in the state of Vermont.[17]

Sandy was responsible for about 150 deaths, approximately half of which occurred in the Northeast.[18] Damages, concentrated in New Jersey, New York, and Connecticut, were estimated at $60 to $80 billion, making Sandy the second most costly Atlantic Hurricane in history behind Katrina.[19] It is also estimated that 650,000 homes were damaged or destroyed, and that 8.5 million people were without power.[18] Floodwaters inundated subway tunnels in New York City (see also Ch. 5: Transportation, "Hurricane Sandy"). Sandy also caused significant damage to the electrical grid and overwhelmed sewage treatment plants.[18] In New Jersey, repairs to damaged power and gas lines are expected to cost about $1 billion, and repairs to waste, water, and sewer systems are expected to cost $3 billion.

Many of these vulnerabilities to coastal flooding and sea level rise (Ch. 2: Our Changing Climate, Key Message 10) and intensifying storms (Ch. 2: Our Changing Climate, Key Messages 8 and 9) – including the projected frequency of flooding of tunnels and airports – were documented as early as 2001 in a report developed in support of the 2000 National Climate Assessment.[20] Despite such reports, the observed vulnerability was a surprise to many coastal residents, which suggests improved communication is needed.

Continued

HURRICANE VULNERABILITY

Over the last decade, cities, states, and agencies in the New York metropolitan region took steps to reduce their vulnerability to coastal storms.[21] In 2008, New York City convened a scientific body of experts – the New York City Panel on Climate Change (NPCC) – and formed a Climate Adaptation Task Force comprised of approximately 40 agencies, private sector companies, and regional groups. A process, approach, and tools for climate change adaptation were developed and documented in New York City[11,22] and New York State.[23] In 2012, the NPCC and Climate Adaptation Task Force were codified into New York City law, a key step towards institutionalizing climate science, impact, and adaptation assessment into long-term planning.[24]

These initiatives led to adaptation efforts, including elevating infrastructure, restoring green spaces, and developing evacuation plans that helped reduce damage and save lives during Irene and Sandy (also see discussion of Hurricane Sandy in Ch. 11: Urban). As rebuilding and recovery advances,[24] decision-making based on current and projected risks from such events by a full set of stakeholders and participants in the entire Northeast could dramatically improve resilience across the region.

Coastal Flooding Along New Jersey's Shore

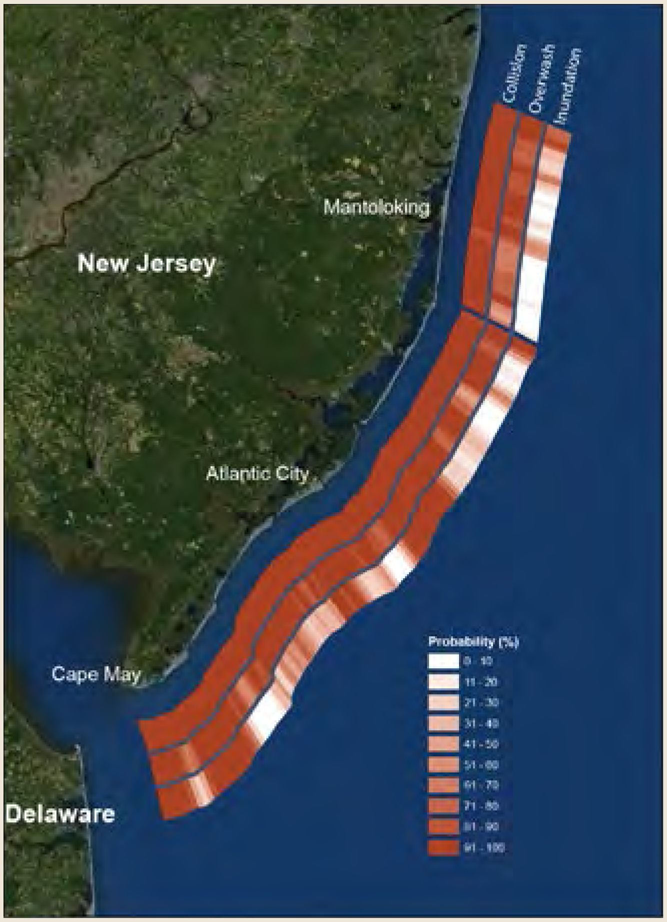

Figure 16.4. Predictions of coastal erosion prior to Sandy's arrival provided the region's residents and decision-makers with advance warning of potential vulnerability. The map shows three bands: collision of waves with beaches causing erosion on the front of the beach; overwash that occurs when water reaches over the highest point and erodes from the rear, which carries sand inland; and inundation, when the shore is severely eroded and new channels can form that lead to permanent flooding. The probabilities are based on the storm striking at high tide. For New Jersey, the model estimated that 21% of the shoreline had more than a 90% chance of experiencing inundation. These projections were realized, and made the New Jersey coastline even more vulnerable to the nor'easter that followed Hurricane Sandy by only 10 days. (Figure source: ESRI and USGS 2012[25]).

Key Message 1: Climate Risks to People

Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.

Urban residents have unique and multifaceted vulnerabilities to heat extremes. Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions (the "urban heat island" effect). During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher[26] than surrounding regions, leading to increased heat-related death among those less able to recover from the heat of the day.[27] Since the hottest days in the Northeast are often associated with high concentrations of ground-level ozone and other pollutants,[28] the combination of heat stress and poor air quality can pose a major health risk to vulnerable groups: young children, the elderly, and those with preexisting health conditions including asthma.[29] Vulnerability is further increased as key infrastructure, including electricity for potentially life-saving air conditioning, is more likely to fail precisely when it is most needed – when demand exceeds available supply. Significant investments may be required to ensure that power generation keeps up with rising demand associated with rising temperatures.[30] Finally, vulnerability to heat waves is not evenly distributed throughout urban areas; outdoor versus indoor air temperatures, air quality, baseline health, and access to air conditioning are all dependent on socioeconomic factors.[29] Socioeconomic factors that tend to increase vulnerability to such hazards include race and ethnicity (being a minority), age (the elderly and children), gender (female), socioeconomic status (low income, status, or poverty), and education (low educational attainment). The condition of human settlements (type of housing and construction, infrastructure, and access to lifelines) and the built environment are also important determinants of socioeconomic vulnerability, especially given the fact that these characteristics influence potential economic losses, injuries, and mortality.[31]

Urban Heat Island

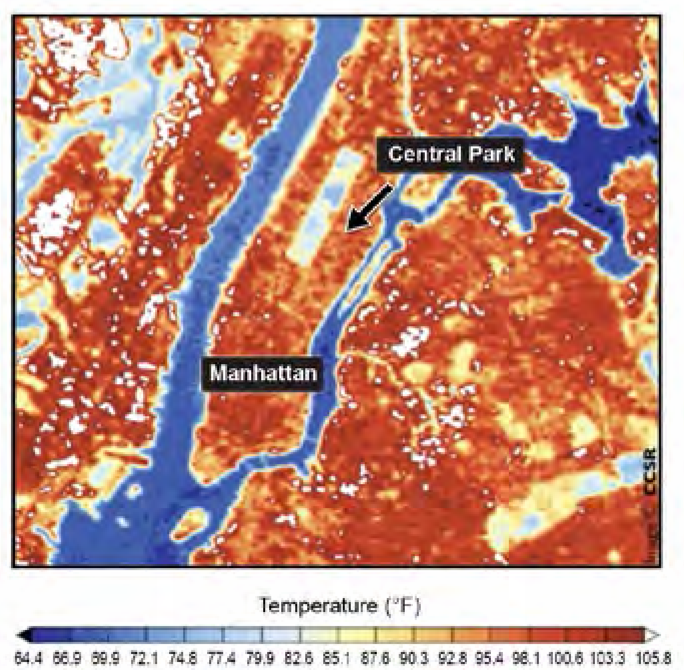

Figure 16.5. Surface temperatures in New York City on a summer's day show the "urban heat island," with temperatures in populous urban areas being approximately 10°F higher than the forested parts of Central Park. Dark blue reflects the colder waters of the Hudson and East Rivers. (Figure source: Center for Climate Systems Research, Columbia University).


©Richard Drew/AP/AP/Corbis

Increased health-related impacts and costs, such as premature death and hospitalization due to even modest increases in heat, are predicted in the Northeast's urban centers (Ch. 9: Human Health).[32] One recent study projected that temperature changes alone would lead to a 50% to 91% increase in heat-related deaths in Manhattan by the 2080s (relative to a 1980s baseline).[33] Increased ground-level ozone due to warming is projected to increase emergency department visits for ozone-related asthma in children (0 to 17 years of age) by 7.3% by the 2020s (given the A2 scenario) relative to a 1990 baseline of approximately 650 visits in the New York metropolitan area.[34]

Heat wave research has tended to focus on urban areas, but vulnerability to heat may also become a major issue in rural areas and small towns because air conditioning is currently not prevalent in parts of the rural Northeast where heat waves have historically been rare. Some areas of northern New England, near the Canadian border, are projected to shift from having less than five to more than 15 days per year over 90°F by the 2050s under the higher emissions scenario (A2) of heat-trapping gases.[3] It should be noted that winter heating needs, a significant expense for many Northeastern residents, are likely to decrease as the century progresses.[35]

The impacts of climate change on public health will extend beyond the direct effects of temperature on human physiology. Changing distributions of temperature, precipitation, and carbon dioxide could affect the potency of plant allergens,[36] and there has been an observed increase of 13 to 27 days in the ragweed pollen season at latitudes above 44°N.[36]

Vector-borne diseases are an additional concern. Most occurrences of Lyme disease in United States are in the Northeast, especially Connecticut.[37] While it is unclear how climate change will impact Lyme disease,[38] several studies in the Northeast have linked tick activity and Lyme disease incidence to climate, specifically abundant late spring and early summer moisture.[39] West Nile Virus (WNV) is another vector-borne disease that may be influenced by changes in climate. Suitable habitat for the Asian Tiger Mosquito, which can transmit West Nile and other vector-borne diseases, is expected to increase in the Northeast from the current 5% to 16% in the next two decades and from 43% to 49% by the end of the century, exposing more than 30 million people to the threat of dense infestations by this species.[40]

Many Northeast cities, including New York, Boston, and Philadelphia, are served by combined sewer systems that collect and treat both stormwater and municipal wastewater. During heavy rain events, combined systems can be overwhelmed and untreated water may be released into local water bodies. In Connecticut, the risk for contracting a stomach illness while swimming significantly increased after a one inch precipitation event,[41] and studies have found associations between diarrheal illness among children and sewage discharge in Milwaukee.[42] More frequent heavy rain events could therefore increase the incidence of waterborne disease.

Historical settlement patterns and ongoing investment in coastal areas and along major rivers combine to increase the vulnerabilities of people in the Northeast to sea level rise and coastal storms. Of the Northeast's population of 64 million,[43] approximately 1.6 million people live within the Federal Emergency Management Agency's (FEMA) 100-year coastal flood zone, with the majority – 63% of those at risk – residing in New York and New Jersey.[44] As sea levels rise, populations in the current 1-in-100-year coastal flood zone (defined as the area with at least a 1% chance of experiencing a coastal flood in a given year) will experience more frequent flooding, and populations that have historically fallen outside the 1-in-100-year flood zone will find themselves in that zone. People living in coastal flood zones are vulnerable to direct loss of life and injury associated with tropical storms and nor'easters. Flood damage to personal property, businesses, and public infrastructure can also result (see Key Message 2).

This risk is not limited to the 1-in-100-year flood zone; in the Mid-Atlantic part of the region alone, estimates suggest that between 450,000 and 2.3 million people are at risk from a three foot sea level rise,[45] which is in the range of projections for this century.

Throughout the Northeast, populations are also concentrated along rivers and their flood plains. In mountainous regions, including much of West Virginia and large parts of Pennsylvania, New York, Vermont, and New Hampshire, more intense precipitation events (Ch. 2: Our Changing Climate)[3] will mean greater flood risk, particularly in valleys, where people, infrastructure, and agriculture tend to be concentrated.

Key Message 2: Stressed Infrastructure

Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.

Disruptions to services provided by public and private infrastructure in the Northeast both interrupt commerce and threaten public health and safety (see also Ch. 11: Urban).[46] In New York State, two feet of sea level rise is estimated (absent adaptation investment) to flood or render unusable 212 miles of roads, 77 miles of rail, 3,647 acres of airport facilities, and 539 acres of runways.[47] Port facilities, such as in Maryland (primarily Baltimore), also have flooding impact estimates: 298 acres, or 32% of the overall port facilities in the state.[47] These impacts have potentially significant economic ramifications. For example, in 2006 alone the Port of Baltimore generated more than 50,200 jobs, $3.6 billion in personal income, $1.9 billion in business revenues, and $388 million in state, county, and municipal tax.[48] The New York City Panel on Climate Change highlighted a broader range of climate impacts on infrastructure sectors (see Table 16.1).[11] Although this study focused specifically on New York City, these impacts are applicable throughout the region. Predicted impacts of coastal flooding on infrastructure were largely borne out by Hurricane Sandy; sea level rise will only increase these vulnerabilities.

The more southern states within the region, including Delaware and Maryland, have a highly vulnerable land area because of a higher rate of sea level rise and relatively flat coastlines compared to the northern tier. The northern states, including Massachusetts, Rhode Island, and Connecticut, have less land area exposed to a high inundation risk because of a lower relative sea level rise and because of their relatively steep coastal terrain.[49] Still, low-lying coastal metropolitan areas in New England have considerable infrastructure at risk. In Boston alone, cumulative damage to buildings and building contents, as well as the associated emergency costs, could potentially be as high as $94 billion between 2000 and 2100, depending on the sea level rise scenario and which adaptive actions are taken.[50]

Table 16.1. Impacts of sea level rise and coastal floods on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig 2010,[51] Zimmerman and Faris 2010,[52] and Ch. 25: Coasts.

Communications	Energy	Transportation	Water and Waste
Higher average sea level			
• Increased saltwater encroachment and damage to low-lying communications infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, causing increased maintenance costs and shortened replacement cycles • Cellular tower destruction or loss of function	• Increased coastal erosion rates and/or permanent inundation of low-lying areas, threatening coastal power plants • Increased equipment damage from corrosive effects of saltwater encroachment, resulting in higher maintenance costs and shorter replacement cycles	• Increased saltwater encroachment and damage to infrastructure not built to withstand saltwater exposure • Increased coastal erosion rates and/or permanent inundation of low-lying areas, resulting in increased maintenance costs and shorter replacement cycles • Decreased clearance levels under bridges	• Increased saltwater encroachment and damage to water and waste infrastructure not built to withstand saltwater exposure • Increased release of pollution and contaminant runoff from sewer systems, treatment plants, brownfields, and waste storage facilities • Permanent inundation of low-lying areas, wetlands, piers, and marine transfer stations • Increased saltwater infiltration into freshwater distribution systems
More frequent and intense coastal flooding			
• Increased need for emergency management actions with high demand on communications infrastructure • Increased damage to communications equipment and infrastructure in low-lying areas	• Increased need for emergency management actions • Exacerbated flooding of low-lying power plants and equipment, as well as structural damage to infrastructure due to wave action • Increased use of energy to control floodwaters • Increased number and duration of local outages due to flooded and corroded equipment	• Increased need for emergency management actions • Exacerbated flooding of streets, subways, tunnel and bridge entrances, as well as structural damage to infrastructure due to wave action • Decreased levels of service from flooded roadways; increased hours of delay from congestion during street flooding episodes • Increased energy use for pumping	• Increased need for emergency management actions • Exacerbated street, basement, and sewer flooding, leading to structural damage to infrastructure • Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

Coney Island after Hurricane Irene

Figure 16.6. Flooded subway tracks in Coney Island after Hurricane Irene. (Photo credit: Metropolitan Transportation Authority of the State of New York 2011).

In the transportation sector (see also Ch. 5: Transportation), many of the region's key highways (including I-95) and rail systems (including Amtrak and commuter rail networks) span areas that are prone to coastal flooding. In addition to temporary service disruptions, storm surge flooding can severely undermine or disable critical infrastructure along coasts, including subway systems, wastewater treatment plants, and electrical substations. Saltwater corrosion can damage sensitive and critical electrical equipment, such as electrical substations for energy distribution and signal equipment for rail systems; corrosion also accelerates rust damage on rail lines. Saltwater also threatens groundwater supplies and damages wastewater treatment plants.

Key Message 3: Agricultural and Ecosystem Impacts

Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.

Farmers in the Northeast are already experiencing consequences of climate change. In addition to direct crop damage from increasingly intense precipitation events, wet springs can delay planting for grain and vegetables in New York, for example, and subsequently delay harvest dates and reduce yields.[53] This is an issue for agriculture nationally,[54] but is particularly acute for the Northeast, where heavy rainfall events have increased more than in any other region of the country (Ch. 2: Our Changing Climate, Key Message 6).[7] In the future, farmers may also face too little water in summer to meet increased crop water demand as summers become hotter and growing seasons lengthen.[55,56] Increased frequency of summer heat stress is also projected, which can negatively affect crop yields and milk production.[57]

Despite a trend toward warmer winters, the risk of frost and freeze damage continues, and has paradoxically increased over the past decade (see also Ch. 8: Ecosystems). These risks are exacerbated for perennial crops in years with variable winter temperatures. For example, midwinter-freeze damage cost wine grape growers in the Finger Lakes region of New York millions of dollars in losses in the winters of 2003 and 2004.[58] This was likely due to de-hardening of the vines during an unusually warm December, which increased susceptibility to cold damage just prior to a subsequent hard freeze. Another avenue for cold damage, even in a relatively warm winter, is when there is an extended warm period in late winter or early spring causing premature leaf-out or bloom, followed by a damaging frost event, as occurred throughout the Northeast in 2007[59] and again in 2012 when apple, grape, cherry, and other fruit crops were hard hit.[60]

Increased weed and pest pressure associated with longer growing seasons and warmer winters will be an increasingly important challenge; there are already examples of earlier arrival and increased populations of some insect pests such as corn earworm.[57] Furthermore, many of the most aggressive weeds, such as kudzu, benefit more than crop plants from higher atmospheric carbon dioxide, and become more resistant to herbicide control.[61] Many weeds respond better than most cash crops to increasing carbon dioxide concentrations, particularly "invasive" weeds with the so-called C_3 photosynthetic pathway, and with rapid and expansive growth patterns, including large allocations of below-ground biomass, such as roots.[62] Research also suggests that glyphosate (for example, Roundup), the most widely-used herbicide in the United States, loses its efficacy on weeds grown at the increased carbon dioxide levels likely to occur in the coming decades.[63] To date, all weed/crop competition studies where the photosynthetic pathway is the same for both species favor weed growth over crop growth as carbon dioxide is increased.[61]

Effects of rising temperatures on the Northeast's ecosystems have already been clearly observed (see also Ch. 8: Ecosystems). Further, changes in species distribution by elevation are occurring; a Vermont study found an upslope shift of 299 to 390 feet in the boundary between northern hardwoods and boreal forest on the western slopes of the Green Mountains between 1964 and 2004.[64] Wildflowers[65] and woody perennials are blooming earlier [66] and migratory birds are arriving sooner.[67] Because species differ in their ability to adjust, asynchronies (like a mismatch between key food source availability and migration patterns) can develop, increasing species and ecosystem vulnerability. Several bird species have expanded their ranges northward[68] as have some invasive insect species, such as the hemlock woolly adelgid,[69] which has devastated hemlock trees. Warmer winters and less snow cover in recent years have contributed to increased deer populations[70] that degrade forest understory vegetation.[71]

As ocean temperatures continue to rise, the range of suitable habitat for many commercially important fish and shellfish species is projected to shift northward. For example, cod and lobster fisheries south of Cape Cod are projected to have significant declines.[72] Although suitable habitats will be shrinking for some species (such as coldwater fish like brook trout) and expanding for others (such as warmwater fish like bass), it is difficult to predict what proportion of species will be able to move or adapt as their optimum climate zones shift.[73] As each species responds uniquely to climate change, disruptions of important species interactions (plants and pollinators; predators and prey) can be expected. For example, it is uncertain what forms of vegetation will move into the Adirondack Mountains when the suitable habitat for spruce-fir forests disappears.[74] Increased productivity of some northern hardwood trees in the Northeast is projected (due to longer growing seasons and assuming a significant benefit from higher atmospheric carbon dioxide), but summer drought and other extreme events may offset potential productivity increases.[75] Range shifts in traditional foods gathered from the forests by Native American communities, such as Wabanaki berries in the Northeast, can have negative health and cultural impacts (Ch. 12: Indigenous Peoples).[76]

In contrast, many insect pests, pathogens, and invasive plants like kudzu appear to be highly and positively responsive to recent and projected climate change.[77] Their expansion will lead to an overall loss of biodiversity, function, and resilience of some ecosystems.

The Northeast's coastal ecosystems and the species that inhabit them are highly vulnerable to rising seas (see also Ch. 25: Coasts, Key Message 4). Beach and dune erosion, both a cause and effect of coastal flooding, is also a major issue in the Northeast.[78,79] Since the early 1800s, there has been an estimated 39% decrease in marsh coverage in coastal New England; in the metropolitan Boston area, marsh coverage is estimated to be less than 20% of its late 1700s value.[80] Impervious urban surfaces and coastal barriers such as seawalls limit the ability of marshes to expand inland as sea levels rise.[81]

THE CHESAPEAKE BAY

The Chesapeake Bay is the largest U.S. estuary, with a drainage basin that extends over six states. It is a critical and highly integrated natural and economic system threatened by changing land-use patterns and a changing climate – including sea level rise, higher temperatures, and more intense precipitation events. The ecosystem has a central role in the economy, including providing sources of food for people and the region's other inhabitants, and cooling water for the energy sector. It also provides critical ecosystem services.

As sea levels rise, the Chesapeake Bay region is expected to experience an increase in coastal flooding and drowning of estuarine wetlands. The lower Chesapeake Bay is especially at risk due to high rates of sinking land (known as subsidence).[82] Climate change and sea level rise are also likely to cause a number of ecological impacts, including declining water quality and clarity, increases in harmful algae and low oxygen (hypoxia) events, decreases in a number of species including eelgrass and seagrass beds, and changing interactions among trophic levels (positions in the food chain) leading to an increase in subtropical fish and shellfish species in the bay.[83]

Key Message 4: Planning and Adaptation

While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.

Of the 12 states in the Northeast, 11 have developed adaptation plans for several sectors and 10 have released, or plan to release, statewide adaptation plans.[84] Given the interconnectedness of climate change impacts and adaptation, multi-state coordination could help to ensure that information is shared efficiently and that emissions reduction and adaptation strategies do not operate at cross-purposes.

Connecticut Coastline and Expanding Salt Marshes

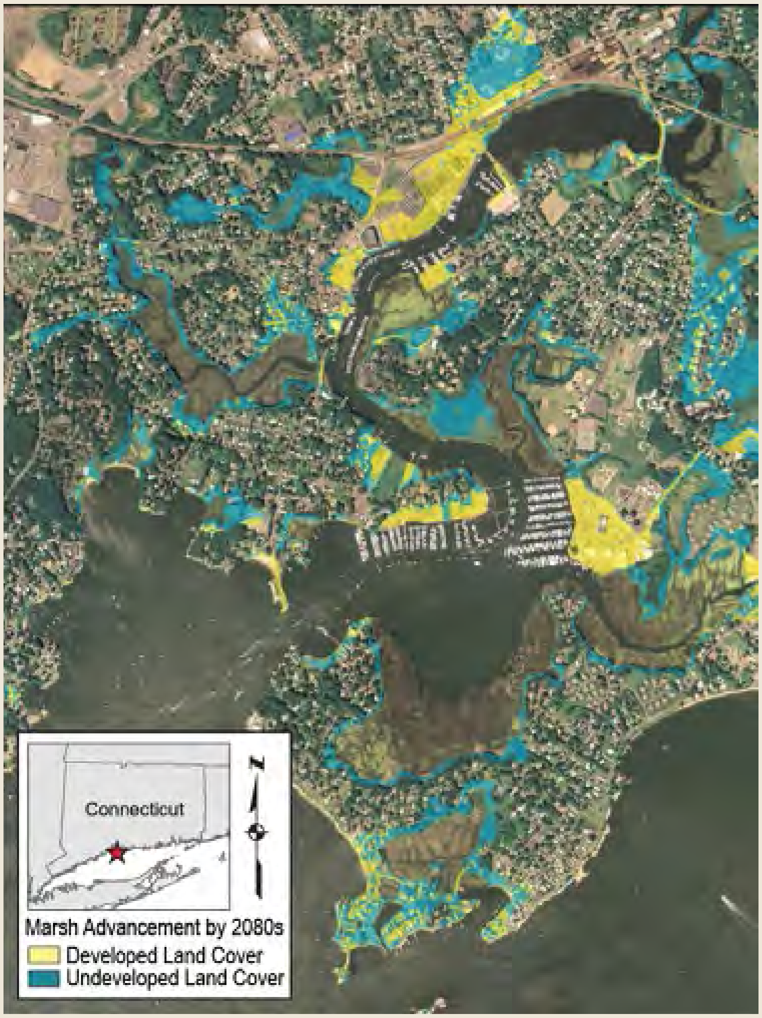

Figure 16.7. The Nature Conservancy's adaptation decision-support tool (www.coastalresilience.org)[88] depicts building-level impacts due to inundation (developed land cover, yellow areas) and potential marsh advancement zones (undeveloped land cover – currently forest, grass, and agriculture – blue areas) using downscaled sea level rise projections (52 inches by 2080s depicted) along the Connecticut and New York coasts. (Figure source: Ferdaña et al. 2010,[90] Beck et al. 2013[89]).

Local and state governments in the Northeast have been leaders and incubators in utilizing legal and regulatory opportunities to foster climate change policies.[85] The Regional Greenhouse Gas Initiative (RGGI) was the first market-based regulatory program in the U.S. aimed at reducing greenhouse gas emissions; it is a cooperative effort among nine northeastern states.[86] Massachusetts became the first state to officially incorporate climate change impacts into its environmental review procedures by adopting legislation that directs agencies to "consider reasonably foreseeable climate change impacts, including additional greenhouse gas emissions, and effects, such as predicted sea level rise."[87] In addition, Maine, Massachusetts, and Rhode Island have each adopted some form of "rolling easement" to ensure that wetlands or dunes migrate inland as sea level rises and reduce the risk of loss of life and property.[45]

Northeast cities have employed a variety of mechanisms to respond to climate change, including land-use planning, provisions to protect infrastructure, regulations related to the design and construction of buildings, and emergency preparation, response, and recovery.[91] While significant progress has been made, local governments still face limitations of legal authority, geographic jurisdiction, and resource constraints that could be addressed through effective engagement and support from higher levels of government.

Keene, New Hampshire, has been a pilot community for ICLEI's Climate Resilient Communities program for adaptation planning[92] – a process implemented through innovative community engagement methods.[93] The Cape Cod Commission is another example in New England; the Commission has drafted model ordinances to help communities incorporate climate into zoning decision-making. Farther south, New York City has taken numerous steps to implement PlaNYC, a far-reaching sustainability plan for the city, including amending the construction code and the zoning laws and the implementation of measures focused on developing adaptation strategies to protect the City's public and private infrastructure from the effects of climate change;[24] some major investments in protection have even been conceptualized.

Storm Surge Barrier

Figure 16.8. Conceptual design of a storm surge barrier in New York City. (Figure source: Jansen and Dircke 2009).

One widely used adaptation-planning template is the eight-step iterative approach developed by the New York City Panel on Climate Change; it was highlighted in the contribution of the National Academy of Science's Adaptation Panel to America's Climate Choices and adopted by the Committee on America's Climate Choices. It describes a procedure that decision-makers at all levels can use to design a flexible adaptation pathway to address infrastructure and other response issues through inventory and assessment of risk. The key, with respect to infrastructure, is to link adaptation strategies with capital improvement cycles and adjustment of plans to incorporate emerging climate projections[11,94] – but the insights are far more general than that (see the Adaptation Panel Report[95]).

In most cases, adaptation requires information and tools coupled to a decision-support process steered by strong leadership, and there are a growing number of examples in the Northeast. At the smaller, municipal scale, coastal pilot projects in Maryland,[96] Delaware,[97] New York, and Connecticut[90] are underway.

Research and outreach efforts are underway in the region to help farmers find ways to cope with a rapidly changing climate, take advantage of a longer growing season, and reduce greenhouse gas emissions,[56,98] but unequal access to capital and information for strategic adaptation and mitigation remain a challenge. Financial barriers can constrain farmer adaptation.[99] Even relatively straightforward adaptations such as changing varieties are not always a low-cost option. Seed for new stress-tolerant varieties is sometimes expensive or regionally unavailable, and new varieties often require investments in new planting equipment or require adjustment in a wide range of farming practices. Investment in irrigation and drainage systems are relatively expensive options, and a challenge for farmers will be determining when the frequency of yield losses due to summer water deficits or flooding has or will become frequent enough to warrant such capital investments.

Regional activities in the Northeast are also being linked to federal efforts. For example, NASA's Agency-wide Climate Adaptation Science Investigator Workgroup (CASI) brings together NASA facilities managers with NASA climate scientists in local Climate Resilience Workshops. This approach was in evidence at the Goddard Space Flight Center in Maryland, where scientists helped institutional managers address energy and stormwater management vulnerabilities.

MAINE'S CULVERTS: AN ADAPTATION CASE STUDY

Culverts and the structures they protect are receiving increasing attention, since they are vulnerable to damage during the types of extreme precipitation events that are occurring with increasing frequency in the Northeast (Ch. 2: Our Changing Climate, Key Message 6; Ch. 5: Transportation). For instance, severe storms in the Northeast that were projected in the 1950s to occur only once in 100 years, now are projected to occur once every 60 years.[100]

The Maine Department of Transportation manages more than 97,000 culverts, but individual property owners or small towns manage even more; Scarborough, Maine, for example, has 2,127 culverts. When 71 town managers and officials in coastal Maine were surveyed as part of the statewide Sustainability Solutions Initiative, culverts, with their 50 to 65 year expected lifespan, emerged atop a wish list for help in adapting to climate change.[101]


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A research initiative that mapped decisions by town managers in Maine to sources of climate information, engineering design, mandated requirements, and calendars identified the complex, multi-jurisdictional challenges of widespread adaptation for even such seemingly simple actions as using larger culverts to carry water from major storms.[101] To help towns adapt culverts to expected climate change over their lifetimes, the Sustainability Solutions Initiative is creating decision tools to map culvert locations, schedule maintenance, estimate needed culvert size, and analyze replacement needs and costs.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

Results of the Northeast Regional Climate assessment workshop that was held on November 17-18, 2011, at Columbia University, with approximately 60 attendees, were critically important in our assessment. The workshop was the beginning of the process that led to the foundational Technical Input Report (TIR).[2] That 313-page report consisted of seven chapters by 13 lead authors and more than 60 authors in total. Public and private citizens or institutions who service and anticipate a role in maintaining support for vulnerable populations in Northeast cities and communities indicated that they are making plans to judge the demand for adaptation services. These stakeholder interactions were surveyed and engaged in the preparation of this chapter. We are confident that the TIR authors made a vigorous attempt to engage various agencies at the state level and non-governmental organizations (NGOs) that have broader perspectives.

The author team engaged in multiple technical discussions via teleconferences, which included careful review of the foundational TIR[2] and approximately 50 additional technical inputs provided by the public, as well as the other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each key message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Northeast Technical Input Report.[2] Nearly 50 Technical Input reports, on a wide range of topics, were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications (including many that are not cited) describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation and river flooding for the Northeast. For sea level rise (SLR), the authors relied on the NCA SLR scenario[12] and research by the authors on the topic (for example, Horton et al. 2010[51]). Recent work[26] summarizes the literature on heat islands and extreme events. For a recent study on climate in the Northeast,[3] the authors worked closely with the region's state climatologists on both the climatology and projections.

The authors also considered many recent peer-reviewed publications[29,32,34,44] that describe how human vulnerabilities to climate hazards in the region can be increased by socioeconomic and other factors. Evaluating coupled multi-system vulnerabilities is an emerging field; as a result, additional sources including white papers[3] have informed this key message as well.

To capture key issues, concerns, and opportunities in the region, various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) and Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf).

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from a prior Northeast assessment[10] (see http://nca2009.globalchange.gov/northeast).

The evidence included results from improved models and updated observational data (for example, Liu et al. 2012; Parris et al. 2012; Sallenger et al. 2012[5,9,12]). The current assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm its relevance and significance for local decision-makers; examples include a Northeast Listening Session in West Virginia, a kickoff meeting in New York City, and New York City Panel on Climate Change meetings.

There is wide diversity of impacts across the region driven by both exposure and sensitivity that are location and socioeconomic context specific. Future vulnerability will be influenced by changes in demography, economics, and policies (development and climate driven) that are difficult to predict and dependent on international and national considerations. Another uncertainty is the potential for adaptation strategies (and to a lesser extent mitigation) to reduce these vulnerabilities.

There are also uncertainties associated with the character of the interconnections among systems, and the positive and negative synergies. For example, a key uncertainty is how systems will respond during extreme events and how people will adjust their short- to long-term planning to take account of a dynamic climate. Such events are, by definition, manifestations of historically rare and therefore relatively undocumented climatology which represent uncertainty in the exposure to climate risk. Nonetheless, these events are correlated, when considered holistically, with climate change driven to some degree by human interference with the climate system. There are uncertainties in exposure.

There are also uncertainties associated with sensitivity to future changes driven to some (potentially significant) degree by non-climate stressors, including background health of the human population and development decisions. Other uncertainties include how much effort will be put into making systems more resilient and the success of these efforts. Another critical uncertainty is associated with the climate system itself.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is:

Very high for sea level rise and coastal flooding as well as heat waves.

High for intense precipitation events and riverine flooding.

Very high for both added stresses on environmental, social, and economic systems and for increased vulnerability, especially for populations that are already most disadvantaged.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.

Description of evidence base

The key message summarizes extensive evidence documented in the Northeast Technical Input Report (TIR).[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

To capture key issues, concerns and opportunities in the region, various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) and Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf).

In addition, a report by the U.S. Department of Transportation[47] provided extensive documentation that augmented an NGO report.[102] Other sources that support this key message include Horton and Rosenzweig, 2010, Rosenzweig et al. 2011, and Zimmerman and Faris, 2010.[23,51,52]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the prior Northeast assessment: (http://nca2009.globalchange.gov/northeast) which informed the prior NCA.[10]

The new sources above relied on improved models that have been calibrated to new observational data across the region.

It is important to note, of course, that there is wide diversity across the region because both exposure and sensitivity are location- and socioeconomic-context-specific. The wisdom derived from many previous assessments by the National Academy of Sciences, the New York Panel on Climate Change, and the 2009 National Climate Assessment[10,11,95] indicates that future vulnerability at any specific location will be influenced by changes in demography, economics, and policy. These changes are difficult to predict at local scales even as they also depend on international and national considerations. The potential for adaptation strategies (and to a lesser extent mitigation) to reduce these vulnerabilities is yet another source of uncertainty that expands as the future moves into the middle of this century.

Assessment of confidence based on evidence

We have **very high** confidence in projected sea level rise and increased coastal flooding, and **high** confidence for increased intense precipitation events. This assessment of confidence is based on our review of the literature and submitted input and has been defended internally and externally in conversation with local decision-makers and representatives of interested NGOs, as well as the extensive interactions with stakeholders across the region reported in the Northeast TIR.[2]

Very high confidence that infrastructure will be increasingly compromised, based on the clear evidence of impacts on current infrastructure from hazards such as Hurricane Irene, and from the huge deficit of needed renewal identified by a diverse engineering community.[46]

KEY MESSAGE #3 TRACEABLE ACCOUNT

Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.

Description of evidence base

The key message summarizes extensive evidence documented in the Northeast Technical Input Report.[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. The Traceable Account for Key Message 1 provides the evidence base on sea level rise, flooding, and precipitation.

Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region with particular focus on managed (agriculture and fisheries) and unmanaged (ecosystems) systems (for example, Buonaiuto et al. 2011; Wolfe et al. 2011[56,70,78]).

Species and ecosystem vulnerability have been well documented historically in numerous peer-reviewed papers in addition to the ones cited in the TIR.[2] There have also been many examples of impacts on agriculture of climate variability and change in the Northeast (for example, Wolfe et al. 2008[57]). Most note that there is potential for significant benefits associated with climate changes to partially offset expected negative outcomes for these managed systems (for example, Hatfield et al. 2011[54])

New information and remaining uncertainties

Important new evidence (cited above, plus Najjar et. al. 2010,[83] for example) confirmed many of the findings from the prior Northeast assessment (http://nca2009.globalchange.gov/northeast) which informed the 2009 NCA.[10] These new sources also relied on improved models that have been calibrated to new observational data across the region.

Agriculture, fisheries, and ecosystems in the Northeast are strongly linked to climate change and to other changes occurring outside the region and beyond the boundaries of the United States. These changes can influence the price of crops and agricultural inputs such as fertilizer, for example, as well as the abundance of ecosystem and agricultural pests and the abundance and range of fish stocks. Other uncertainties include imprecise understandings of how complex ecosystems will respond to climate- and non-climate-induced changes and the extent to which organisms may be able to adapt to a changing climate.

Assessment of confidence based on evidence

Based on our assessment, we have **very high** confidence for climate impacts (especially sea level rise and storm surge) on ecosystems; and we have **high** confidence for climate impacts on agriculture (reduced to some degree, compared to our level of confidence about ecosystems, by uncertainty about the efficacy and implementation of adaptation options). Confidence in fisheries changes is **high** since confidence in both ocean warming and fish sensitivity to temperature is **high**.

KEY MESSAGE #4 TRACEABLE ACCOUNT

While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.

Description of evidence base

The key message relies heavily on extensive evidence documented in the Northeast Technical Input Report (TIR).[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Many of the key references cited in the TIR reflected experiences and processes developed in iterative stakeholder engagement concerning risk management[94,103] that have been heavily cited and employed in new venues – local communities like Keane (NH) and New York City, for example.

Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region (for example, for Delaware, Maine, Maryland, and Long Island, NY). In addition, there have been agency and government white paper reports describing proposed adaptation strategies based on climate impact assessments.[11,90] We discovered that 10 of the 12 states in the Northeast have statewide adaptation plans in place or under development (many plans can be found at: http://georgetownclimate.org/node/3324).

New information and remaining uncertainties

That most Northeast states have begun to plan for adaptation is a matter of record. That few adaptation plans have been implemented is confirmed in Technical Inputs submitted to the National Climate Assessment process as well as prior assessments (http://nca2009.globalchange.gov/northeast), which informed the 2009 NCA.[10]

Key uncertainties looking forward include: 1) the extent to which proposed adaptation strategies will be implemented given a range of factors including competing demands and limited funding; 2) the role of the private sector and individual action in adaptation, roles which can be difficult to document; 3) the extent of the federal role in adaptation planning and implementation; and 4) how changes in technology and the world economy may change the feasibility of specific adaptation strategies.[11]

Assessment of confidence based on evidence

This Key Message is simply a statement of observed fact, so confidence language is not applicable.

Climate Change Impacts in the United States

CHAPTER 17
SOUTHEAST AND THE CARIBBEAN

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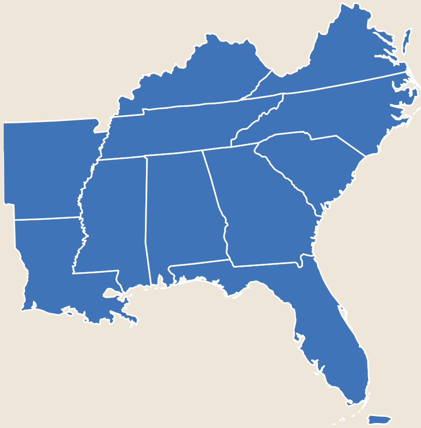

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On the Web: http://nca2014.globalchange.gov/report/regions/southeast

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

17 SOUTHEAST
AND THE CARIBBEAN

Key Messages

1. **Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.**
2. **Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.**
3. **Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.**

The Southeast and Caribbean are exceptionally vulnerable to sea level rise, extreme heat events, hurricanes, and decreased water availability. The geographic distribution of these impacts and vulnerabilities is uneven, since the region encompasses a wide range of natural system types, from the Appalachian Mountains to the coastal plains. It is also home to more than 80 million people[1] and draws millions of visitors every year. In 2009, Puerto Rico hosted 3.5 million tourists who spent $3.5 billion.[2] In 2012, Louisiana and Florida alone hosted more than 115 million visitors.[3]

The region has two of the most populous metropolitan areas in the country (Miami and Atlanta) and four of the ten fastest-growing metropolitan areas.[1] Three of these (Palm Coast, FL, Cape Coral-Fort Myers, FL, and Myrtle Beach area, SC) are along the coast and are vulnerable to sea level rise and storm surge. Puerto Rico has one of the highest population densities in the world, with 56% of the population living in coastal municipalities.[4]

The Gulf and Atlantic coasts are major producers of seafood and home to seven major ports[5] that are also vulnerable. The Southeast is a major energy producer of coal, crude oil, and natural gas, and is the highest energy user of any of the National Climate Assessment regions.[5]

The Southeast's climate is influenced by many factors, including latitude, topography, and proximity to the Atlantic Ocean


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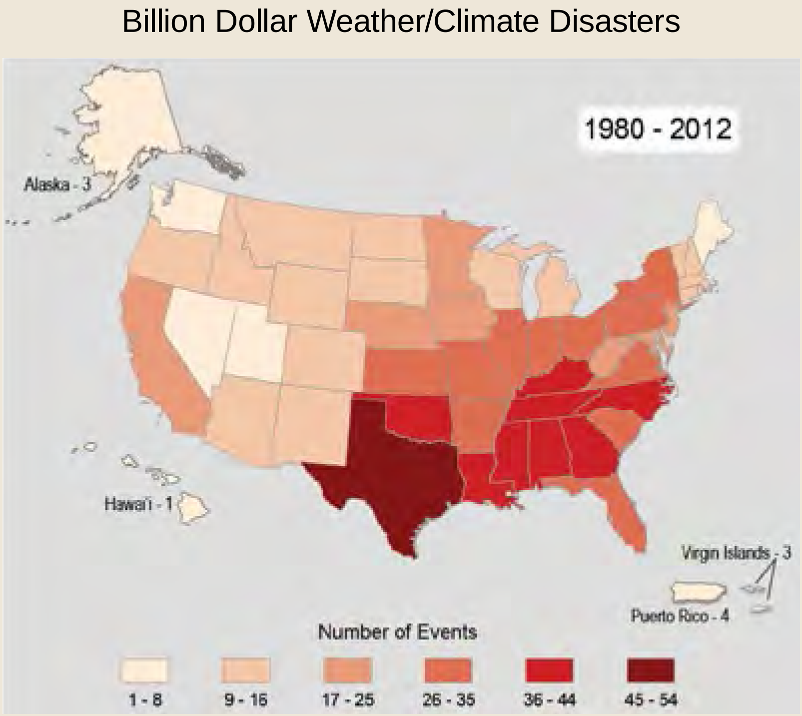

Figure 17.1. This map summarizes the number of times each state has been affected by weather and climate events over the past 30 years that have resulted in more than a billion dollars in damages. The Southeast has been affected by more billion-dollar disasters than any other region. The primary disaster type for coastal states such as Florida is hurricanes, while interior and northern states in the region also experience sizeable numbers of tornadoes and winter storms. For a list of events and the affected states, see: http://www.ncdc.noaa.gov/billions/events.[6] (Figure source: NOAA NCDC).

STORIES OF CHANGE: COASTAL LOUISIANA TRIBAL COMMUNITIES

Climate change impacts, especially sea level rise and related increases in storm surges pulsing farther inland, will continue to exacerbate ongoing land loss already affecting Louisiana tribes. Four Native communities in Southeast Louisiana (Grand Bayou Village, Grand Caillou/Dulac, Isle de Jean Charles, and Pointe-au-Chien) have already experienced significant land loss. Management of river flow has deprived the coastal wetlands of the freshwater and sediment that they need to replenish and persist. Dredging of canals through marshes for oil and gas exploration and pipelines has led to erosion and intense saltwater intrusion, resulting in additional land loss. Due to these and other natural and man-made problems, Louisiana has lost 1,880 square miles of land in the last 80 years.[8] This combination of changes has resulted in a cascade of losses of sacred places, healing plants, habitat for important wildlife, food security,[9] and in some cases connectivity with the mainland. Additional impacts include increased inundation of native lands, further travel to reach traditional fishing grounds, reduced connections among family members as their lands have become more flood-prone and some have had to move, and declining community cohesiveness as heat requires more indoor time.[10] (For more specifics, see Ch. 12: Indigenous Peoples). Numerous other impacts from increases in temperature, sea level rise, land loss, erosion, subsidence, and saltwater intrusion amplify these existing problems.

Shrinking Lands for Tribal Communities

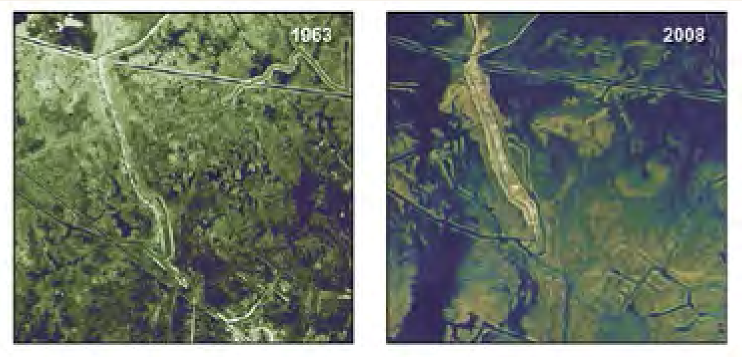

Figure 17.2. Aerial photos of Isle de Jean Charles in Louisiana taken 25 years apart shows evidence of the effects of rising seas, sinking land, and human development. The wetlands adjacent to the Isle de Jean Charles community (about 60 miles south of New Orleans) have been disappearing rapidly since the photo on the left was taken in 1963. By 2008, after four major hurricanes, significant erosion, and alteration of the surrounding marsh for oil and gas extraction, open water surrounds the greatly reduced dry land. See Ch. 25: Coasts for more information. (Photo credit: USGS).

and the Gulf of Mexico. Temperatures generally decrease northward and into mountain areas, while precipitation decreases with distance from the Gulf and Atlantic coasts. The region's climate also varies considerably over seasons, years, and decades, largely due to natural cycles such as the El Niño-Southern Oscillation (ENSO – periodic changes in ocean surface temperatures in the Tropical Pacific Ocean), the semi-permanent high pressure system over Bermuda, differences in atmospheric pressure over key areas of the globe, and landfalling tropical weather systems.[7] These cycles alter the occurrences of hurricanes, tornadoes, droughts, flooding, freezing winters, and ice storms, contributing to climate and weather disasters in the region that have exceeded the total number of billion dollar disasters experienced in all other regions of the country combined (see Figure 17.1).

Observed and Projected Climate Change

Average annual temperature during the last century across the Southeast cycled between warm and cool periods (see Figure 17.3, black line). A warm peak occurred during the 1930s and 1940s followed by a cool period in the 1960s and 1970s. Temperatures increased again from 1970 to the present by an average of 2°F, with higher average temperatures during summer months. There have been increasing numbers of days above 95°F and nights above 75°F, and decreasing numbers of extremely cold days since 1970.[11] The Caribbean also exhibits a trend since the 1950s, with increasing numbers of very warm days and nights, and with daytime maximum temperatures above 90°F and nights above 75°F.[4] Daily and five-day rainfall intensities have also increased.[5] Also, summers have been either increasingly dry or extremely wet.[11] For the Caribbean, precipitation trends are unclear, with some regions experiencing smaller annual amounts of rainfall and some increasing amounts.[4] Although the number of major tornadoes has increased over the last 50 years, there is no statistically significant trend (Ch 2: Our Changing Climate, Key Message 9).[11,12] This increase may be attributable to better reporting of tornadoes. The number of Category 4 and 5 hurricanes in the Atlantic basin has increased substantially since the early 1980s compared to the historical record that dates back to the mid-1880s (Ch. 2: Our Changing Climate, Key Message 8). This can be attributed to both natural variability and climate change.

Southeast Temperature: Observed and Projected

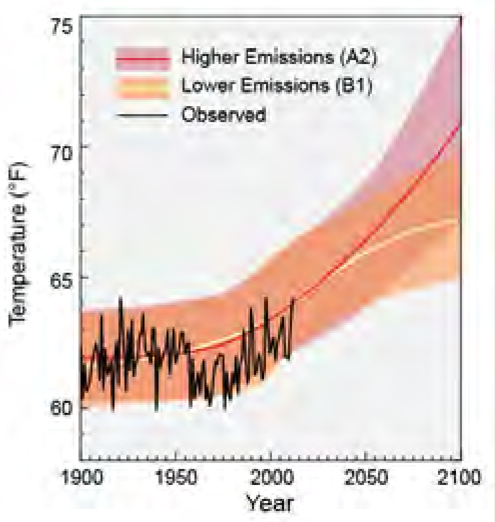

Figure 17.3. Observed annual average temperature for the Southeast and projected temperatures assuming substantial emissions reductions (lower emissions, B1) and assuming continued growth in emissions (higher emissions, A2).[11] For each emissions scenario, shading shows the range of projections and the line shows a central estimate. The projections were referenced to observed temperatures for the period 1901-1960. The region warmed during the early part of last century, cooled for a few decades, and is now warming again. The lack of an overall upward trend over the entire period of 1900-2012 is unusual compared to the rest of the U.S. and the globe. This feature has been dubbed the "warming hole" and has been the subject of considerable research, although a conclusive cause has not been identified. (Figure source: adapted from Kunkel et al. 2013[11]).

Temperatures across the Southeast and Caribbean are expected to increase during this century, with shorter-term (year-to-year and decade-to-decade) fluctuations over time due to natural climate variability (Ch. 2: Our Changing Climate, Key Message 3).[4] Major consequences of warming include significant increases in the number of hot days (95°F or above) and decreases in freezing events. Although projected increases for some parts of the region by the year 2100 are generally smaller than for other regions of the United States, projected increases for interior states of the region are larger than coastal regions by 1°F to 2°F. Regional average increases are in the range of 4°F to 8°F (combined 25th to 75th percentile range for A2 and B1 emissions scenarios) and 2°F to 5°F for Puerto Rico.[11]

Projected Change in Number of Days Over 95°F

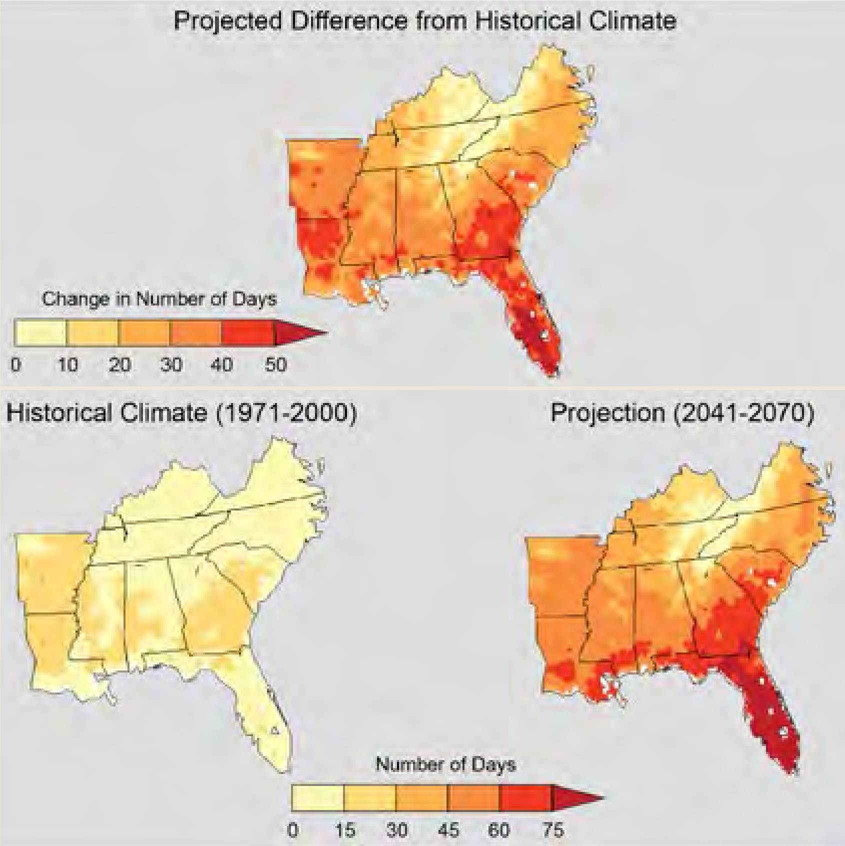

Figure 17.4. Projected average number of days per year with maximum temperatures above 95°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario). Patterns are similar, but less pronounced, assuming a reduced emissions scenario (B1). (Figure source: NOAA NCDC / CICS-NC).

Projections of future precipitation patterns are less certain than projections for temperature increases.[11] Because the Southeast is located in the transition zone between projected wetter conditions to the north and drier conditions to the southwest, many of the model projections show only small changes relative to natural variations. However, many models do project drier conditions in the far southwest of the region and wetter conditions in the far northeast of the region, consistent with the larger continental-scale pattern of wetness and dryness (Ch. 2: Our Changing Climate, Key Message 5).[11] For the Caribbean, it is equally difficult to project the magnitude of precipitation changes, although the majority of models show future decreases in precipitation are likely, with a few areas showing increases. In general, annual average decreases are likely to be spread across the entire region.[4] Projections further suggest that warming will cause tropical storms to be fewer in number globally, but stronger in force, with more Category 4 and 5 storms (Ch. 2: Our Changing Climate, Key Message 8).[13] On top of the large increases in extreme precipitation observed during last century and early this century (Ch. 2: Our Changing Climate, Figures 2.16, 2.17, and 2.18), substantial further increases are projected as this century progresses (Ch. 2: Our Changing Climate, Figure 2.19).

Projected Change in Number of Nights Below 32°F

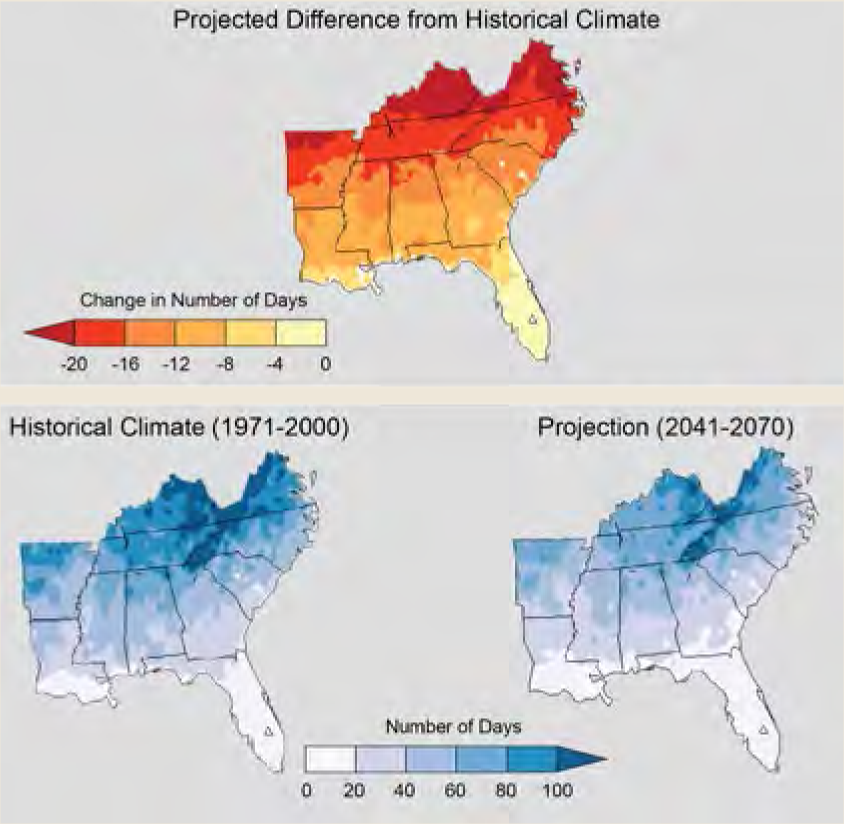

Figure 17.5. Projected average number of days per year with temperatures less than 32°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario). Patterns are similar, but less pronounced, assuming a reduced emissions scenario (B1). (Figure source: NOAA NCDC / CICS-NC).

Key Message 1: Sea Level Rise Threats

Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.

Global sea level rise over the past century averaged approximately eight inches (Ch. 2: Our Changing Climate, Key Message 10),[14,15] and that rate is expected to accelerate through the end of this century.[16] Portions of the Southeast and Caribbean are highly vulnerable to sea level rise.[4,5] How much sea level rise is experienced in any particular place depends on whether and how much the local land is sinking (also called subsidence) or rising, and changes in offshore currents.[16,17]

Large numbers of cities, roads, railways, ports, airports, oil and gas facilities, and water supplies are at low elevations and potentially vulnerable to the impacts of sea level rise. New Orleans (with roughly half of its population living below sea level[19]), Miami, Tampa, Charleston, and Virginia Beach are among those most at risk.[20] As a result of current sea level rise, the coastline of Puerto Rico around Rincón is being eroded at a rate of 3.3 feet per year.[4]

According to a recent study co-sponsored by a regional utility, coastal counties and parishes in Alabama, Mississippi, Louisiana, and Texas, with a population of approximately 12 million, assets of about $2 trillion, and producers of $634 billion in annual gross domestic product, already face significant losses that annually average $14 billion from hurricane winds, land subsidence, and sea level rise. Future losses for the 2030 timeframe could reach $18 billion (with no sea level rise or change in hurricane wind speed) to $23 billion (with a nearly 3% increase in hurricane wind speed and just under 6 inches of sea level rise). Approximately 50% of the increase in the estimated losses is related to climate change. The study identified $7 billion in cost-effective adaptation investments that could reduce estimated annual losses by about 30% in the 2030 timeframe.[21]

The North Carolina Department of Transportation is raising the roadbed of U.S. Highway 64 across the Albemarle-Pamlico Peninsula by four feet, which includes 18 inches to allow for high-

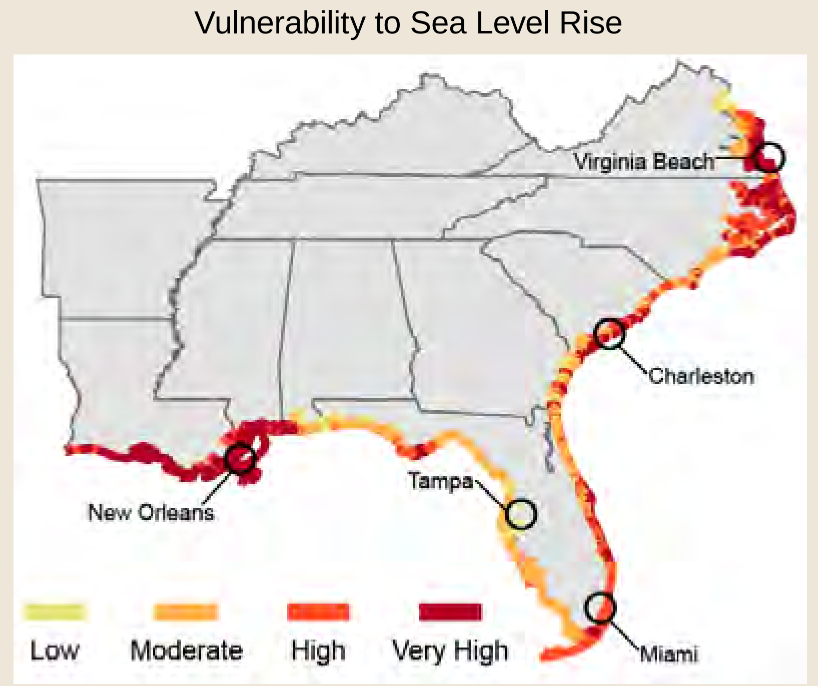

Figure 17.6. The map shows the relative risk that physical changes will occur as sea level rises. The Coastal Vulnerability Index used here is calculated based on tidal range, wave height, coastal slope, shoreline change, landform and processes, and historical rate of relative sea level rise. The approach combines a coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, and yields a relative measure of the system's natural vulnerability to the effects of sea level rise. (Data from Hammar-Klose and Thieler 2001[18]).

er future sea levels.[22] Louisiana State Highway 1, heavily used for delivering critical oil and gas resources from Port Fourchon, is literally sinking, resulting in more frequent and more severe flooding during high tides and storms.[8] The Department of Homeland Security estimated that a 90-day shutdown of this road would cost the nation $7.8 billion.[23]

Sea level rise increases pressure on utilities – such as water and energy – by contaminating potential freshwater supplies with saltwater. Such problems are amplified during extreme dry periods with little runoff. Uncertainties in the scale, timing, and location of climate change impacts can make decision-making difficult, but response strategies, especially those that try to anticipate possible unintended consequences, can be more effective with early planning. Some utilities in the region are already taking sea level rise into account in the construction of new facilities and are seeking to diversify their water sources.[24]

There is an imminent threat of increased inland flooding during heavy rain events in low-lying coastal areas such as southeast Florida, where just inches of sea level rise will impair the capacity of stormwater drainage systems to empty into the ocean.[24] Drainage problems are already being experienced in many locations during seasonal high tides, heavy rains, and storm surge events. Adaptation options that are being assessed in this region include the redesign and improvement of storm drainage canals, flood control structures, and stormwater pumps.

As temperatures and sea levels increase, changes in marine and coastal systems are expected to affect the potential for energy resource development in coastal zones and the outer continental shelf. Oil and gas production infrastructure in bays and coves that are protected by barrier islands, for example, are likely to become increasingly vulnerable to storm surge as sea level rises and barrier islands deteriorate along the central Gulf Coast. The capacity for expanding and maintaining onshore and offshore support facilities and transportation networks is also apt to be affected.[25]

Sea level rise and storm surge can have impacts far beyond the area directly affected. Homes and infrastructure in low areas are increasingly prone to flooding during tropical storms. As a result, insurance costs may increase or coverage may become unavailable[26] and people may move from vulnerable areas, stressing the social and infrastructural capacity of surrounding areas. This migration also happens in response to extreme events such as Hurricane Katrina, when more than 200,000 migrants were temporarily housed in Houston and 42% indicated they would try to remain there (Ch. 9: Human Health, Figure 9.10).[27]

Homes and infrastructure in low-lying areas are increasingly vulnerable to flooding due to storm surge as sea level rises.

Highway 1 to Port Fourchon: Vulnerability of a Critical Link for U.S. Oil

Figure 17.7. Highway 1 in southern Louisiana is the only road to Port Fourchon, whose infrastructure supports 18% of the nation's oil and 90% of the nation's offshore oil and gas production. Flooding is becoming more common on Highway 1 in Leeville (inset photo from flooding in 2004), on the way to Port Fourchon. See also Ch. 25: Coasts, Figure 25.5. (Figure and photo sources: Louisiana Department of Transportation and Development; State of Louisiana 2012[8]).

Furthermore, because income is a key indicator of climate vulnerability, people that have limited economic resources are more likely to be adversely affected by climate change impacts such as sea level rise. In the Gulf region, nearly 100% of the "most socially vulnerable people live in areas unlikely to be protected from inundation," bringing equity issues and environmental justice into coastal planning efforts.[28]

Ecosystems of the Southeast and Caribbean are exposed to and at risk from sea level rise, especially tidal marshes and swamps. Some tidal freshwater forests are already retreating, while mangrove forests (adapted to coastal conditions) are expanding landward.[29] The pace of sea level rise will increasingly lead to inundation of coastal wetlands in the region. Such a crisis in land loss has occurred in coastal Louisiana for several decades, with 1,880 square miles having been lost since the 1930s as a result of natural and man-made factors.[8,30] With tidal wetland loss, protection of coastal lands and people against storm surge will be compromised.

Reduction of wetlands also increases the potential for losses of important fishery habitat. Additionally, ocean warming could support shifts in local species composition, invasive or new locally viable species, changes in species growth rates, shifts in migratory patterns or dates, and alterations to spawning seasons.[4,31] Any of these could affect the local or regional seafood output and thus the local economy.

In some southeastern coastal areas, changes in salinity and water levels due to a number of complex interactions (including subsidence, availability of sediment, precipitation, and sea level rise) can happen so fast that local vegetation cannot adapt quickly enough and those areas become open water.[32] Fire, hurricanes, and other disturbances have similar effects, causing ecosystems to cross thresholds at which dramatic changes occur over short time frames.[33]

The impacts of sea level rise on agriculture derive from decreased freshwater availability, land loss, and saltwater intrusion. Saltwater intrusion is projected to reduce the availability of fresh surface and groundwater for irrigation, thereby limiting crop production in some areas.[34] Agricultural areas around Miami-Dade County and southern Louisiana with shallow groundwater tables are at risk of increased inundation and future loss of cropland with a projected loss of 37,500 acres in Florida with a 27-inch sea level rise,[35] which is well within the 1- to 4-foot range of sea level rise projected by 2100 (Ch. 2: Our Changing Climate, Key Message 10).

There are basically three types of adaptation options to rising sea levels: protect (such as building levees or other "hard" methods), accommodate (such as raising structures or using "soft" or natural protection measures such as wetlands restoration), and retreat.[15,32] Individuals and communities are using all of these strategies. However, regional cooperation among local, state, and federal governments can greatly improve the success of adapting to impacts of climate change and sea level rise. An excellent example is the Southeast Florida Regional Compact. Through collaboration of county, state, and federal agencies, a comprehensive action plan was developed that includes hundreds of actions and special Adaptation Action Areas.[37]

South Florida: Uniquely Vulnerable to Sea Level Rise

Figure 17.8. Sea level rise presents major challenges to South Florida's existing coastal water management system due to a combination of increasingly urbanized areas, aging flood control facilities, flat topography, and porous limestone aquifers. For instance, South Florida's freshwater well field protection areas (left map: pink areas) lie close to the current interface between saltwater and freshwater (red line), which will shift inland with rising sea level, affecting water managers' ability to draw drinking water from current resources. Coastal water control structures (right map: yellow circles) that were originally built about 60 years ago at the ends of drainage canals to keep saltwater out and to provide flood protection to urbanized areas along the coast are now threatened by sea level rise. Even today, residents in some areas such as Miami Beach are experiencing seawater flooding their streets (lower photo). (Maps from The South Florida Water Management District.[36] Photo credit: Luis Espinoza, Miami-Dade County Department of Regulatory and Economic Resources).

Key Message 2: Increasing Temperatures

Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.

The negative effects of heat on human cardiovascular, cerebral, and respiratory systems are well established (Ch. 9: Human Health)(for example: Kovats and Hajat 2008; O'Neill and Ebi 2009[38]). Atlanta, Miami, New Orleans, and Tampa have already had increases in the number of days with temperatures exceeding 95°F, during which the number of deaths is above average.[39] Higher temperatures also contribute to the formation of harmful air pollutants and allergens.[40] Ground-level ozone is projected to increase in the 19 largest urban areas of the Southeast, leading to an increase in deaths.[41] A rise in hospital admissions due to respiratory illnesses, emergency room visits for asthma, and lost school days is expected.[42]

The climate in many parts of the Southeast and Caribbean is suitable for mosquitoes carrying malaria and yellow and dengue fevers. The small island states in the Caribbean already have a high health burden from climate-sensitive disease, including vector-borne and zoonotic (animal to human) diseases.[43] It is still uncertain how regional climate changes will affect vector-borne and zoonotic disease transmissions. While higher temperatures are likely to shorten both development and incubation time,[44] vectors (like disease-carrying insects) also need

Local Planning

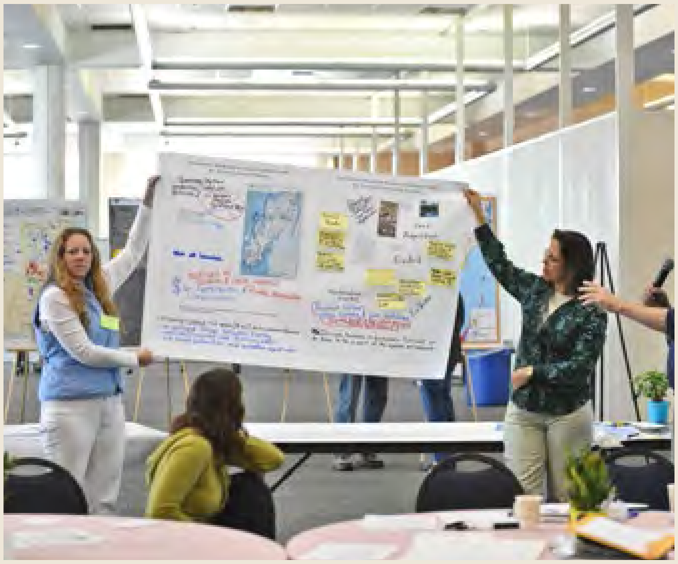

Figure 17.9. Miami-Dade County staff leading workshop on incorporating climate change considerations in local planning. (Photo credit: Armando Rodriguez, Miami-Dade County).

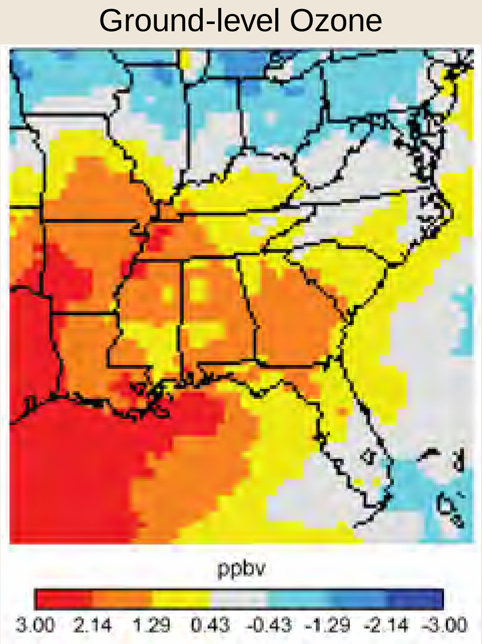

Figure 17.10. Ground-level ozone is an air pollutant that is harmful to human health and which generally increases with rising temperatures. The map shows projected changes in average annual ground level ozone pollution concentration in 2050 as compared to 2001, using a mid-range emissions scenario (A1B, which assumes gradual reductions from current emissions trends beginning around mid-century). (Figure source: adapted from Tagaris et al. 2009[42]).

the right conditions for breeding (water), for dispersal (vegetation and humidity), and access to susceptible vertebrate hosts to complete the disease transmission cycle.[5] While these transmission cycles are complex, increasing temperatures have the potential to result in an expanded region with more favorable conditions for transmission of these diseases.[45,46]

Climate change is expected to increase harmful algal blooms and several disease-causing agents in inland and coastal waters, which were not previously problems in the region.[47,48,49] For instance, higher sea surface temperatures are associated with higher rates of ciguatera fish poisoning,[48,50] one of the most common hazards from algal blooms in the region.[51] The algae that causes this food-borne illness is moving northward, following increasing sea surface temperatures.[52] Certain species of bacteria (*Vibrio,* for example) that grow in warm coastal waters and are present in Gulf Coast shellfish can cause infections in humans. Infections are now frequently reported both earlier and later by one month than traditionally observed.[53]

Coral reefs in the Southeast and Caribbean, as well as worldwide, are susceptible to climate change, especially warming waters and ocean acidification, whose impacts are exacerbated when coupled with other stressors, including disease, runoff, over-exploitation, and invasive species.[4,5]

An expanding population and regional land-use changes have reduced land available for agriculture and forests faster in the Southeast than in any other region in the contiguous United States.[54] Climate change is also expected to change the unwanted spread and locations of some non-native plants, which will result in new management challenges.[55]

Heat stress adversely affects dairy and livestock production.[56] Optimal temperatures for milk production are between 40ºF and 75ºF, and additional heat stress could shift dairy production northward.[57] A 10% decline in livestock yield is projected across the Southeast with a 9ºF increase in temperatures (applied as an incremental uniform increase in temperature between 1990 and 2060), related mainly to warmer summers.[58]

Summer heat stress is projected to reduce crop productivity, especially when coupled with increased drought (Ch. 6: Agriculture). The 2007 drought cost the Georgia agriculture industry $339 million in crop losses,[59] and the 2002 drought cost the agricultural industry in North Carolina $398 million.[5] A 2.2ºF increase in temperature would likely reduce overall productivity for corn, soybeans, rice, cotton, and peanuts across the South – though rising CO_2 levels could partially offset these decreases based on a crop yield simulation model.[60] In Georgia, climate projections indicate corn yields could decline by 15% and wheat yields by 20% through 2020.[61] In addition, many fruit crops from long-lived trees and bushes require chilling periods and may need to be replaced in a warming climate.[60]

Adaptation for agriculture involves decisions at many scales, from infrastructure investments (like reservoirs) to management decisions (like cropping patterns).[62] Dominant adaptation strategies include altering local planting choices to better match new climate conditions[62] and developing heat-tolerant crop varieties and breeds of livestock.[5,57] Most critical for effective adaptation is the delivery of climate risk information to decision-makers at appropriate temporal and spatial scales[57,62] and a focus on cropping systems that increase water-use efficiency, shifts toward irrigation, and more precise control of irrigation delivery (see also Ch. 28: Adaptation, Table 28.6).[5,57]

The southeastern U.S. (data include Texas and Oklahoma, not Puerto Rico) leads the nation in number of wildfires, averaging 45,000 fires per year,[63] and this number continues to increase.[64,65] Increasing temperatures contribute to increased fire frequency, intensity, and size,[63] though at some level of fire frequency, increased fire frequency would lead to decreased fire intensity. Lightning is a frequent initiator of wildfires,[66] and the Southeast currently has the greatest frequency of lightning strikes of any region of the country.[67] Increasing temperatures and changing atmospheric patterns may affect the number of lightning strikes in the Southeast, which could influence air quality, direct injury, and wildfires. Drought often correlates with large wildfire events, as seen with the Okeefenokee (2007) and Florida fires (1998). The 1998 Florida fires led to losses of more than $600 million.[68] Wildfires also affect human health through reduced air quality and direct injuries.[68,69,70] Expanding population and associated land-use fragmentation will limit the application of prescribed burning, a useful adaptive strategy.[65] Growth management could enhance the ability to pursue future adaptive management of forest fuels.

Forest disturbances caused by insects and pathogens are altered by climate changes due to factors such as increased tree stress, shifting phenology, and altered insect and pathogen lifecycles.[71] Current knowledge provides limited insights into specific impacts on epidemics, associated tree growth and mortality, and economic loss in the Southeast, though the overall extent and virulence of some insects and pathogens have been on the rise (for example, Hemlock Woolly Adelgid in the Southern Appalachians), while recent declines in southern pine beetle (*Dendroctonus frontalis* Zimmerman) epidemics in Louisiana and East Texas have been attributed to rising temperatures.[72] Due to southern forests' vast size and the high cost of management options, adaptation strategies are limited, except through post-epidemic management responses – for example, sanitation cuts and species replacement.

The Southeast has the existing power plant capacity to produce 32% of the nation's electricity.[73] Energy use is approximately 27% of the U.S. total, more than any other region.[5] Net energy demand is projected to increase, largely due to higher temperatures and increased use of air conditioning. This will potentially stress electricity generating capacity, distribution infrastructure, and energy costs. Energy costs are of particular concern for lower income households, the elderly, and other vulnerable communities, such as native tribes.[5,10] Long periods of extreme heat could also damage roadways by softening asphalt and cause deformities of railroad tracks, bridge joints, and other transportation infrastructure.[74]

Increasing temperatures will affect many facets of life in the Southeast and Caribbean region. For each impact there could be many possible responses. Many adaptation responses are described in other chapters in this document. For examples, please see the sector chapter of interest and Ch. 28: Adaptation.

Key Message 3: Water Availability

Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.

Water resources in the Southeast are abundant and support heavily populated urban areas, rural communities, unique ecosystems, and economies based on agriculture, energy, and tourism. The region also experiences extensive droughts, such as the 2007 drought in Atlanta, Georgia, that created water conflicts among three states.[11,75] In northwestern Puerto Rico, water was rationed for more than 200,000 people during the winter and spring of 1997-1998 because of low reservoir levels.[76] Droughts are one of the most frequent climate hazards in the Caribbean, resulting in economic losses.[77] Water supply and demand in the Southeast and Caribbean are influenced by many changing factors, including climate (for example, temperature increases that contribute to increased transpiration from plants and evaporation from soils and water bodies), population, and land use.[4,5] While change in projected precipitation for this region has high uncertainty (Ch. 2: Our Changing Climate), there is still a reasonable expectation that there will be reduced water availability due to the increased evaporative losses resulting from rising temperatures alone.

With projected increases in population, the conversion of rural areas, forestlands, and wetlands into residential, commercial, industrial, and agricultural zones is expected to intensify.[54] The continued development of urbanized areas will increase water demand, exacerbate saltwater intrusion into freshwater aquifers, and threaten environmentally sensitive wetlands bordering urban areas.[24]

Additionally, higher sea levels will accelerate saltwater intrusion into freshwater supplies from rivers, streams, and groundwater sources near the coast. The region's aquaculture industry also may be compromised by climate-related stresses on groundwater quality and quantity.[78] Porous aquifers in some areas make them particularly vulnerable to saltwater intrusion.[36,79] For example, officials in the city of Hallandale Beach, Florida, have already abandoned six of their eight drinking water wells.[80]

With increasing demand for food and rising food prices, irrigated agriculture will expand in some states. Also, population expansion in the region is expected to increase domestic water demand. Such increases in water demand by the energy, agricultural, and urban sectors will increase the competition for water, particularly in situations where environmental water needs conflict with other uses.[5]

As seen from Figure 17.11, the net water supply availability in the Southeast is expected to decline over the next several decades, particularly in the western part of the region.[82] Analysis of current and future water resources in the Caribbean shows

Trends in Water Availability

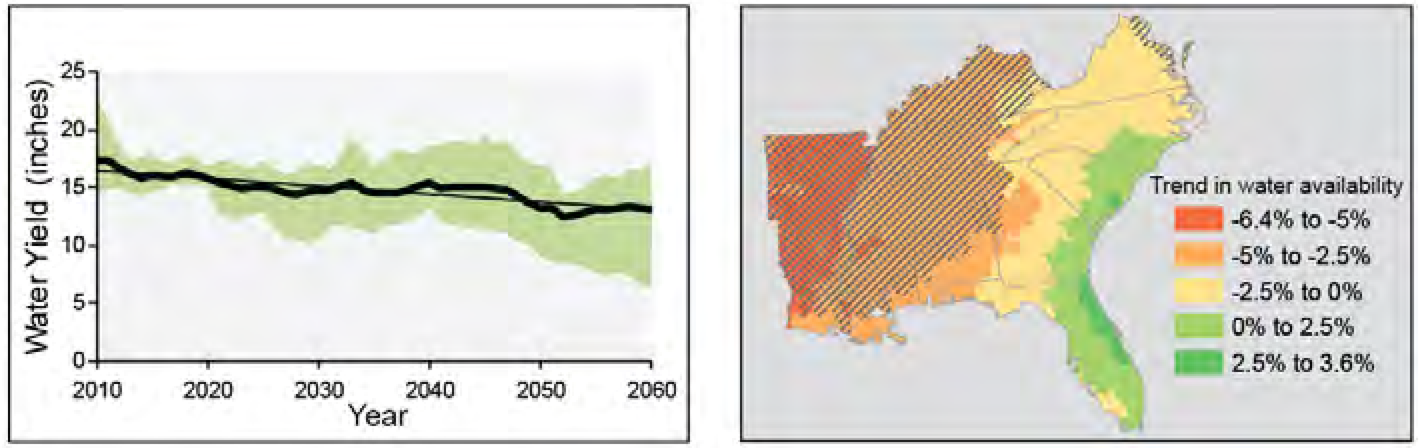

Figure 17.11. Left: Projected trend in Southeast-wide annual water yield (equivalent to water availability) due to climate change. The green area represents the range in predicted water yield from four climate model projections based on the A1B and B2 emissions scenarios. Right: Spatial pattern of change in water yield for 2010-2060 (decadal trend relative to 2010). The hatched areas are those where the predicted negative trend in water availability associated with the range of climate scenarios is statistically significant (with 95% confidence). As shown on the map, the western part of the Southeast region is expected to see the largest reductions in water availability. (Figure source: adapted from Sun et al. 2013[82]).

many of the small islands would be exposed to severe water stress under all climate change scenarios.[83]

New freshwater well fields may have to be established inland to replenish water supply lost from existing wells closer to the ocean once they are compromised by saltwater intrusion. Programs to increase water-use efficiency, reuse of wastewater, and water storage capacity are options that can help alleviate water supply stress.

The Southeast and Caribbean, which has a disproportionate number of the fastest-growing metropolitan areas in the country and important economic sectors located in low-lying coastal areas, is particularly vulnerable to some of the expected impacts of climate change. The most severe and widespread impacts are likely to be associated with sea level rise and changes in temperature and precipitation, which ultimately affect water availability. Changes in land use and land cover, more rapid in the Southeast and Caribbean than most other areas of the country, often interact with and serve to amplify the effects of climate change on regional ecosystems.

A Southeast River Basin Under Stress

Figure 17.12. The Apalachicola-Chattahoochee-Flint River Basin in Georgia exemplifies a place where many water uses are in conflict, and future climate change is expected to exacerbate this conflict.[84] The basin drains 19,600 square miles in three states and supplies water for multiple, often competing, uses, including irrigation, drinking water and other municipal uses, power plant cooling, navigation, hydropower, recreation, and ecosystems. Under future climate change, this basin is likely to experience more severe water supply shortages, more frequent emptying of reservoirs, violation of environmental flow requirements (with possible impacts to fisheries at the mouth of the Apalachicola), less energy generation, and more competition for remaining water. Adaptation options include changes in reservoir storage and release procedures and possible phased expansion of reservoir capacity.[84,85] Additional adaptation options could include water conservation and demand management. (Figure source: Georgakakos et al. 2010[84]).

WATER RECYCLING

Because of Clayton County, Georgia's, innovative water recycling project during the 2007-2008 drought, they were able to maintain reservoirs at near capacity and an abundant supply of water while neighboring Lake Lanier, the water supply for Atlanta, was at record lows. Clayton County developed a series of constructed wetlands used to filter treated water that recharges groundwater and supplies surface reservoirs. They have also implemented efficiency and leak detection programs[81] (for additional specific information see the Clayton County Water Authority website at: http://www.ccwa.us/).

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages
A central component of the process was the Southeast Regional Climate Assessment Workshop that was held on September 26-27, 2011, in Atlanta, with approximately 75 attendees. This workshop began the process leading to a foundational Technical Input Report (TIR). That 341-page foundational "Southeast Region Technical Report to the National Climate Assessment"[5] comprised 14 chapters from over 100 authors, including all levels of government, non-governmental organizations, and business.

The writing team held a 2-day meeting in April 2012 in Ft. Lauderdale, engaged in multiple teleconference and webinar technical discussions, which included careful review of the foundational TIR,[5] nearly 60 additional technical inputs provided by the public, and other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the Southeast chapter writing team and lead author of each key message.

Key message #1 Traceable Account

Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.

Description of evidence base
The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report.[5] A total of 57 technical inputs on a wide range of southeast-relevant topics (including sea level rise) were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that the rate of sea level rise has increased is based on satellite altimetry data and direct measurements such as tide gauges (Ch. 2: Our Changing Climate, Key Message 10). Numerous peer-reviewed publications describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation for the Southeast.[5] For sea level rise, the authors relied on the NCA Sea Level Change Scenario[16] and detailed discussion in the foundational TIR.[5]

Evidence that sea level rise is a threat to natural and human environments is documented in detail within the foundational TIR[5] and other technical inputs, as well as considerable peer-reviewed literature (for example, Campanella 2010).[19] Field studies document examples of areas that are being flooded more regularly, saltwater intrusion into fresh water wells,[80] and changes from fresh to saltwater in coastal ecosystems (for example, freshwater marshes) causing them to die,[32] and increases in vulnerability of many communities to coastal erosion. Economic impacts are seen in the cost to avoid flooded roads, buildings, and ports;[23] the need to drill new fresh water wells;[80] and the loss of coastal ecosystems and their storm surge protection.

New information and remaining uncertainties
Tremendous improvement has been made since the last Intergovernmental Panel on Climate Change evaluation of sea level rise in 2007,[86] with strong evidence of mass loss of Greenland icecap and glaciers worldwide (Ch. 2: Our Changing Climate). Improved analyses of tide gauges, coastal elevations, and circulation changes in offshore waters have also provided new information on accelerating rates of rise (Ch. 2: Our Changing Climate, Figure 2.26). These have been documented in the NCA Sea Level Change Scenario publication.[16]

Uncertainties in the rate of sea level rise through this century stems from a combination of large differences in projections among different climate models, natural climate variability, uncertainties in the melting of land-based glaciers and the Antarctic and Greenland ice sheets especially, and uncertainties about future rates of fossil fuel emissions. A further key uncertainty is the rate of vertical land movement at specific locations. The two factors – sea level rise and subsidence – when combined, increase the impact of global sea level rise in any specific area. A third area of uncertainty is where and what adaptive plans and actions are being undertaken to avoid flooding and associated impacts on people, communities, facilities, infrastructure, and ecosystems.

Assessment of confidence based on evidence
Sea level is expected to continue to rise for several centuries, even if greenhouse gas emissions are stabilized, due to the time it takes for the ocean to absorb heat energy from the atmosphere. Because sea levels determine the locations of human activities and

ecosystems along the coasts, increases in sea level and in the rate of rise will nearly certainly have substantial impacts on natural and human systems along the coastal area. What specific locations will be impacted under what specific levels of sea level rise needs to be determined location-by-location. However, given that many locations are already being affected by rising seas, more and more locations will be impacted as sea levels continue to rise. Confidence in this key message is therefore judged to be very high.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report.[5] Technical inputs (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe increasing hazards associated with heat events and rising temperatures for the Southeast. The authors of a report on the Southeast climate[11] worked closely with the region's state climatologists on both the climatology and projections for temperature and associated heat events. Evidence of rising temperatures and current impacts[38,39] is based on an extensive set of field measurements.

There is considerable evidence of the effects of high air temperatures across a wide range of natural and managed systems in the Southeast. Increased temperatures affect human health and hospital admissions.[38,40,42]

Rising water temperatures also increase risks of bacterial infection from eating Gulf Coast shellfish[53] and increase algal blooms that have negative human health effects.[47,48] There is also evidence that there will be an increase in favorable conditions for mosquitoes that carry diseases.[46] Higher temperatures are detrimental to natural and urban environments, through increased wildfires in natural areas and managed forests[63,64,65,70] and increased invasiveness of some non-native plants.[55] High temperatures also contribute to more roadway damage and deformities of transportation infrastructure such as railroad tracks and bridges (Ch. 5: Transportation).[74] In addition, high temperatures increase net energy demand and costs, placing more stress on electricity generating plants and distribution infrastructure.

Increasing temperatures in the Southeast cause more stresses on crop and livestock agricultural systems. Heat stress reduces dairy and livestock production[56] and also reduces yields of various crops grown in this region (corn, soybean, peanuts, rice, and cotton).[60,61]

New information and remaining uncertainties

Since 2007, studies on impacts of higher temperatures have increased in many areas. Most of the publications cited above concluded that increasing temperatures in the Southeast will result in negative impacts on human health, the natural and built environments, energy, agriculture, and forestry.

A key issue (uncertainty) is the detailed mechanistic responses, including adaptive capacities and/or resilience, of natural and built environments, the public health system, energy systems, agriculture, and forests to increasing temperatures and extreme heat events.

Another uncertainty is how combinations of stresses, for example lack of water in addition to extreme heat, will affect outcomes. There is a need for more monitoring to document the extent and location of vulnerable areas (natural and human), and then research to assess how those impacts will affect productivity of key food and forest resources and human well-being. There is also a need for research that develops or identifies more resilient, adapted systems.

Assessment of confidence based on evidence

Increasing Temperatures: There is **high** confidence in documentation that projects increases in air temperatures (but not in the precise amount) and associated increases in the frequency, intensity, and duration of extreme heat events. Projections for increases in temperature are more certain in the Southeast than projections of changes in precipitation.

Impacts of increasing temperatures: Rising temperatures and the substantial increase in duration of high temperatures (for either the low [B1] or high [A2] emissions scenarios) above critical thresholds will have significant impacts on the population, agricultural industries, and ecosystems in the region. There is **high** confidence in documentation that increases in temperature in the Southeast will result in higher risks of negative impacts on human health, agricultural, and forest production; on natural systems; on the built environment; and on energy demand. There is **lower** confidence in the magnitude of these impacts, partly due to lack of information on how these systems will adapt (without human intervention) or be adapted (by people) to higher temperatures, and partly due to the limited knowledge base on the wide diversity that exists across this region in climates and human and natural systems.

Key message #3 Traceable Account

Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report (TIR).[5] Technical inputs (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Chapter 2, Our Changing Climate, describes evidence for drought and precipitation in its key messages. Numerous salient studies support the key message of decreased water availability, as summarized for the Southeast in the TIR.[5]

Evidence for the impacts on the region's economy and unique ecosystems is also detailed in the TIR[5] and the broader literature surveyed by the authors.[77]

New information and remaining uncertainties

Many studies have been published since 2007 documenting increasing demands for water in the Southeast due to increases in populations and irrigated agriculture, in addition to water shortages due to extensive droughts.[5,11] There is also new evidence of losses in fresh water wells near coastlines due to saltwater intrusion[79,80] and of continuing conflicts among states for water use, particularly during drought periods.[5,84]

It is a virtual certainty that population growth in the Southeast will continue in the future and will be accompanied by a significant change in patterns of land use, which is projected to include a larger fraction of urbanized areas, reduced agricultural areas, and reduced forest cover.[54] With increasing population and human demand, competition for water among the agriculture, urban, and environment sectors is projected to continue to increase. However, the projected population increases for the lower (B1) versus higher (A2) emissions scenarios differ significantly (33% versus 151%).[11] Consequently, the effect of climate change on urban water demand for the lower emissions scenario is projected to be much lower than for that of the higher emissions scenario. Land-use change will also alter the regional hydrology significantly. Unless measures are adopted to increase water storage, availability of freshwater during dry periods will decrease, partly due to drainage and other human activities.

Projected increase in temperature will increase evaporation, and in areas (the western part of the region[87]) where precipitation is projected to decrease in response to climate change, the net amount of water supply for human and environmental uses may decrease significantly.

Along the coastline of the Southeast, accelerated intrusion of saltwater due to sea level rise will impact both freshwater well fields and potentially freshwater intakes in rivers and streams connected to the ocean. Although sea level rise (SLR) corresponding to the higher emissions scenario is much higher (twice as much), even the SLR for the lower emissions scenario will increasingly impact water supply availability in low-lying areas of the region, as these areas are already being impacted by SLR and land subsidence.

Projections of specific spatial and temporal changes in precipitation in the Southeast remain highly uncertain and it is important to know with a reasonable confidence the sign and the magnitude of this change in various parts of the large Southeast region.

For the Southeast, there are no reliable projections of evapotranspiration, another major factor that determines water yield. This adds to uncertainty about water availability.

There are inadequate regional studies at basin scales to determine the future competition for water supply among sectors (urban, agriculture, and environment).

There is a need for more accurate information on future changes in drought magnitude and frequency.

Assessment of confidence based on evidence

There is **high** confidence in each aspect of the key message: it is virtually certain that the water demand for human consumption in the Southeast will increase as a result of population growth. The past evidence of impacts during droughts and the projected changes in drivers (land-use change, population growth, and climate change) suggest that there is a **high** confidence of the above assessment of future water availability. However, without additional studies, the resilience and the adaptive capacity of the socioeconomic and environmental systems are not known.

Water supply is critical for sustainability of the region, particularly in view of increasing population and land-use changes. Climate models' precipitation projections are uncertain. Nonetheless, the combined effects of possible decreases in precipitation, increasing evaporation losses due to warming, and increasing demands for water due to higher populations (under either lower [B1] or higher [A2] emissions scenarios) will have a significant impact on water availability for all sectors.

Climate Change Impacts in the United States

CHAPTER 18
MIDWEST

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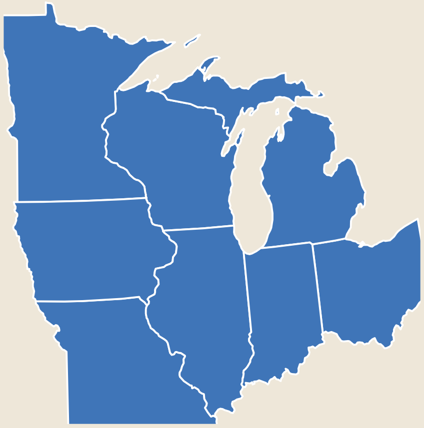

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On the Web: http://nca2014.globalchange.gov/report/regions/midwest

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

18 MIDWEST

KEY MESSAGES

1. **In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.**
2. **The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.**
3. **Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.**
4. **The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.**
5. **Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.**
6. **Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.**

The Midwest has a population of more than 61 million people (about 20% of the national total) and generates a regional gross domestic product of more than $2.6 trillion (about 19% of the national total).[1] The Midwest is home to expansive agricultural lands, forests in the north, the Great Lakes, substantial industrial activity, and major urban areas, including eight of the nation's 50 most populous cities. The region has experienced shifts in population, socioeconomic changes, air and water pollution, and landscape changes, and exhibits multiple vulnerabilities to both climate variability and climate change.

In general, climate change will tend to amplify existing climate-related risks from climate to people, ecosystems, and infrastructure in the Midwest (Ch. 10: Energy, Water, and Land). Direct effects of increased heat stress, flooding, drought, and late spring freezes on natural and managed ecosystems may be multiplied by changes in pests and disease prevalence, increased competition from non-native or opportunistic native species, ecosystem disturbances, land-use change, landscape fragmentation, atmospheric pollutants, and economic shocks such as crop failures or reduced yields due to extreme weather events. These added stresses, when taken collectively, are projected to alter the ecosystem and socioeconomic patterns and processes in ways that most people in the region would consider detrimental. Much of the region's fisheries, recreation, tourism, and commerce depend on the Great Lakes and expansive northern forests, which already face pollution and invasive species pressure that will be exacerbated by climate change.

Most of the region's population lives in cities, which are particularly vulnerable to climate change related flooding and life-threatening heat waves because of aging infrastructure and other factors. Climate change may also augment or intensify other stresses on vegetation encountered in urban environments, including increased atmospheric pollution, heat island effects, a highly variable water cycle, and frequent exposure to new pests and diseases. Some cities in the region are already engaged in the process of capacity building or are actively building resilience to the threats posed by climate change. The region's highly energy-intensive economy emits a disproportionately large amount of the gases responsible for warming

Temperatures are Rising in the Midwest

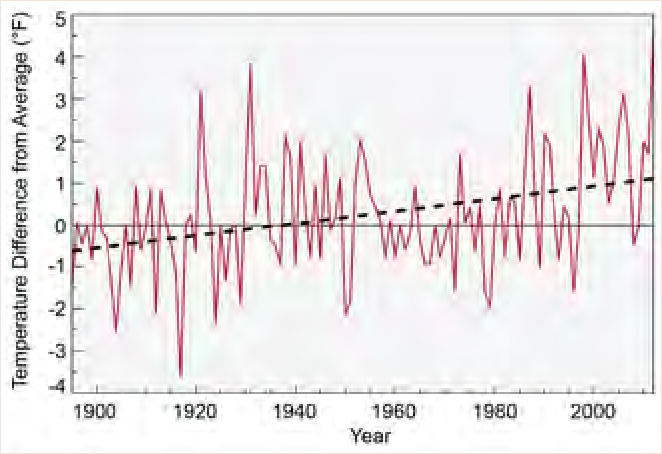

Figure 18.1. Annual average temperatures (red line) across the Midwest show a trend towards increasing temperature. The trend (dashed line) calculated over the period 1895-2012 is equal to an increase of 1.5°F. (Figure source: updated from Kunkel et al. 2013[4]).

the climate (called greenhouse gases or heat-trapping gases). But as discussed below, it also has a large and increasingly realized potential to reduce these emissions.

The rate of warming in the Midwest has markedly accelerated over the past few decades. Between 1900 and 2010, the average Midwest air temperature increased by more than 1.5°F (Figure 18.1). However, between 1950 and 2010, the average temperature increased twice as quickly, and between 1980 and 2010, it increased three times as quickly as it did from 1900 to 2010.[1] Warming has been more rapid at night and during winter. These trends are consistent with expectations of increased concentrations of heat-trapping gases and observed changes in concentrations of certain particles in the atmosphere.[1,2]

The amount of future warming will depend on changes in the atmospheric concentration of heat-trapping gases. Projections for regionally averaged temperature increases by the middle of the century (2046-2065) relative to 1979-2000 are approximately 3.8°F for a scenario with substantial emissions reductions (B1) and 4.9°F with continued growth in global emissions (A2). The projections for the end of the century (2081-2100) are approximately 5.6°F for the lower emissions scenario and 8.5°F for the higher emissions scenario (see Ch. 2: Our Changing Climate, Key Message 3).[3]

In 2011, 11 of the 14 U.S. weather-related disasters with damages of more than $1 billion affected the Midwest.[5] Several types of extreme weather events have already increased in frequency and/or intensity due to climate change, and further increases are projected (Ch. 2: Our Changing Climate, Key Message 7).[6]

Key Message 1: Impacts to Agriculture

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Agriculture dominates Midwest land use, with more than two-thirds of land designated as farmland.[3] The region accounts for about 65% of U.S. corn and soybean production,[7] mostly from non-irrigated lands.[1] Corn and soybeans constitute 85% of Midwest crop receipts, with high-value crops such as fruits and vegetables making up most of the remainder.[8] Corn and soybean yields increased markedly (by a factor of more than 5) over the last century largely due to technological innovation, but are still vulnerable to year-to-year variations in weather conditions.[9]

The Midwest growing season lengthened by almost two weeks since 1950, due in large part to earlier occurrence of the last spring freeze.[10] This trend is expected to continue,[3,11] though the potential agricultural consequences are complex and vary by crop. For corn, small long-term average temperature increases will shorten the duration of reproductive development, leading to yield declines,[12] even when offset by carbon dioxide (CO_2) stimulation.[13] For soybeans, yields have a two in three chance of increasing early in this century due to CO_2 fertilization, but these increases are projected to be offset later in the century by higher temperature stress[14] (see Figure 18.2 for projections of increases in the frost-free season length and the number of summer days with temperatures over 95°F).

Future crop yields will be more strongly influenced by anomalous weather events than by changes in average temperature or annual precipitation (Ch. 6: Agriculture). Cold injury due to a freeze event after plant budding can decimate fruit crop production,[15] as happened in 2002, and again in 2012, to Michigan's $60 million tart cherry crop. Springtime cold air outbreaks (at least two consecutive days during which the daily average surface air temperature is below 95% of the simulated average wintertime surface air temperature) are projected to continue to occur throughout this century.[16] As a result, increased productivity of some crops due to higher temperatures, longer growing seasons, and elevated CO_2 concentrations could be offset by increased freeze damage.[17] Heat waves during pollination of field crops such as corn and soybean also reduce yields (Figure 18.3).[12] Wetter springs may reduce crop yields and profits,[18] especially if growers are forced to switch to late-planted, shorter-season varieties. A recent study suggests the volatility of U.S. corn prices is more sensitive to near-term climate change than to energy policy influences or to use of agricultural products for energy production, such as biofuel.[19]

Agriculture is responsible for about 8% of U.S. heat-trapping gas emissions,[20] and there is tremendous potential for farming practices to reduce emissions or store more carbon in soil.[21] Although large-scale agriculture in the Midwest historically led to decreased carbon in soils, higher crop residue inputs and adoption of different soil management techniques have reversed this trend. Other techniques, such as planting cover crops and no-till soil management, can further increase CO_2 uptake and reduce energy use.[22,23] Use of agricultural best management practices can also improve water quality by reducing the loss of sediments and nutrients from farm fields. Methane released from animals and their wastes can be reduced by altered diets and methane capture systems, and nitrous oxide production can be reduced by judicious fertilizer use[24] and improved waste handling.[21] In addition, if biofuel crops are grown sustainably,[25] they offer emissions reduction opportunities by substituting for fossil fuel-based energy (Ch. 10: Energy, Water, and Land).

Projected Mid-Century Temperature Changes in the Midwest

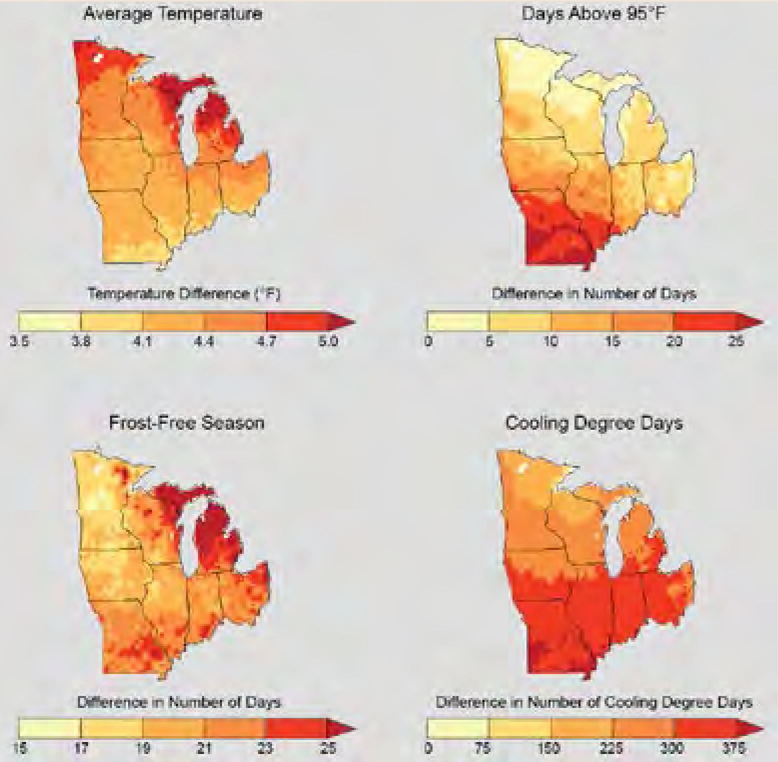

Figure 18.2. Projected increase in annual average temperatures (top left) by mid-century (2041-2070) as compared to the 1971-2000 period tell only part of the climate change story. Maps also show annual projected increases in the number of the hottest days (days over 95°F, top right), longer frost-free seasons (bottom left), and an increase in cooling degree days (bottom right), defined as the number of degrees that a day's average temperature is above 65°F, which generally leads to an increase in energy use for air conditioning. Projections are from global climate models that assume emissions of heat-trapping gases continue to rise (A2 scenario). (Figure source: NOAA NCDC / CICS-NC).

Crop Yields Decline under Higher Temperatures

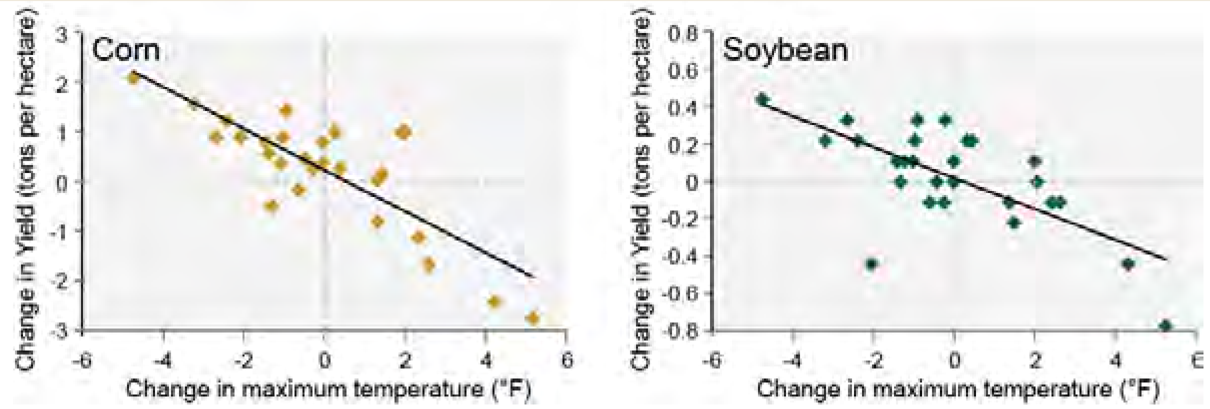

Figure 18.3. Crop yields are very sensitive to temperature and rainfall. They are especially sensitive to high temperatures during the pollination and grain filling period. For example, corn (left) and soybean (right) harvests in Illinois and Indiana, two major producers, were lower in years with average maximum summer (June, July, and August) temperatures higher than the average from 1980 to 2007. Most years with below-average yields are both warmer and drier than normal.[26,27] There is high correlation between warm and dry conditions during Midwest summers[28] due to similar meteorological conditions and drought-caused changes.[29] (Figure source: Mishra and Cherkauer 2010[26]).

Key Message 2: Forest Composition

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

The Midwest is characterized by a rich diversity of native species juxtaposed on one of the world's most productive agricultural systems.[30] The remnants of intact natural ecosystems in the region,[31] including prairies, forests, streams, and wetlands, are rich with varied species.[32] The combined effects of climate change, land-use change, and increasing numbers of invasive species are the primary threats to Midwest natural ecosystems.[33] Species most vulnerable to climate change include those that occur in isolated habitats; live near their physiological tolerance limits; have specific habitat requirements, low reproductive rates, or limited dispersal capability; are dependent on interactions with specific other species; and/or have low genetic variability.[34]

Among the varied ecosystems of the region, forest systems are particularly vulnerable to multiple stresses. The habitat ranges of many iconic tree species such as paper birch, quaking aspen, balsam fir, and black spruce are projected to decline substantially across the northern Midwest as they shift northward, while species that are common farther south, including several oaks and pines, expand their ranges northward into the region (Figure 18.4).[35,36] There is considerable variability in the likelihood of a species' habitat changing and the adaptability of the species with regard to climate change.[37] Migration to accommodate changed habitat is expected to be slow for many Midwest species, due to relatively flat topography, high latitudes, and fragmented habitats including the Great Lakes barrier. To reach areas that are 1.8°F cooler, species in mountainous terrains need to shift 550 feet higher in altitude (which can be achieved in only a few miles), whereas species in flat terrain like the Midwest must move as much as 90 miles north to reach a similarly cooler habitat.[38]

Although global forests currently capture and store more carbon each year than they emit,[39] the ability of forests to act as large, global carbon absorbers ("sinks") may be reduced by projected increased disturbances from insect outbreaks,[40] forest fire,[41] and drought,[42] leading to increases in tree mortality and carbon emissions. Some regions may even shift from being a carbon sink to being an atmospheric carbon dioxide source,[43,44] though large uncertainties exist, such as whether projected disturbances to forests will be chronic or episodic.[45] Midwest forests are more resilient to forest carbon losses than most western forests because of relatively high moisture availability, greater nitrogen deposition (which tends to act as a fertilizer), and lower wildfire risk.[43,46]

Forest Composition Shifts

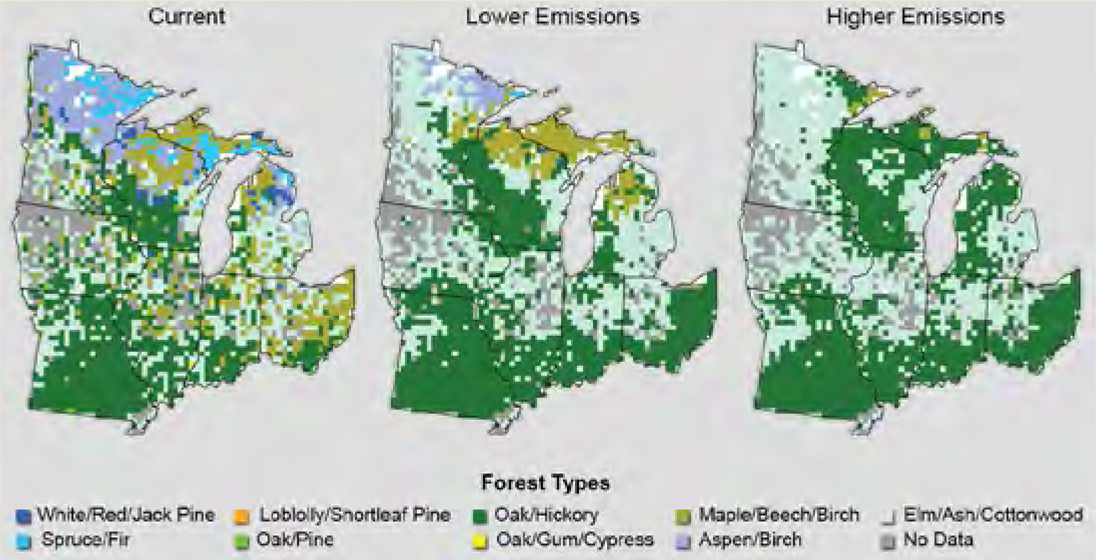

Figure 18.4. As climate changes, species can often adapt by changing their ranges. Maps show current and projected future distribution of habitats for forest types in the Midwest under two emissions scenarios, a lower scenario that assumes reductions in heat-trapping gas emissions (B1), and a very high scenario that assumes continued increases in emissions (A1FI). Habitats for white/red/jack pine, maple/beech/birch, spruce/fir, and aspen/birch forests are projected to greatly decline from the northern forests, especially under higher emissions scenarios, while various oak forest types are projected to expand.[37] While some forest types may not remain dominant, they will still be present in reduced quantities. Therefore, it is more appropriate to assess changes on an individual species basis, since all species within a forest type will not exhibit equal responses to climate change. (Figure source: Prasad et al. 2007[37]).

Key Message 3: Public Health Risks

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

The frequency of major heat waves in the Midwest has increased over the last six decades.[47] For the United States, mortality increases 4% during heat waves compared with non-heat wave days.[48] During July 2011, 132 million people across the U.S. were under a heat alert – and on July 20 of that year, the majority of the Midwest experienced temperatures in excess of 100°F. Heat stress is projected to increase as a result of both increased summer temperatures and humidity.[49,50] One study projected an increase of between 166 and 2,217 excess deaths per year from heat wave-related mortality in Chicago alone by 2081-2100.[51] The lower number assumes a climate scenario with significant reductions in emissions of greenhouse gases (B1), while the upper number assumes a scenario under which emissions continue to increase (A2). These projections are significant when compared to recent Chicago heat waves, where 114 people died from the heat wave of 1999 and about 700 died from the heat wave of 1995.[52] Heat response plans and early warning systems save lives, and from 1975 to 2004, mortality rates per heat event declined.[53] However, many municipalities lack such plans.[54]

More than 20 million people in the Midwest experience air quality that fails to meet national ambient air quality standards.[1] Degraded air quality due to human-induced emissions[55] and increased pollen season duration[56] are projected to be amplified with higher temperatures,[57] and pollution and pollen exposures, in addition to heat waves, can harm human health (Ch. 9: Human Health). Policy options exist (for example, see "Alternative Transportation Options Create Multiple Benefits") that could reduce emissions of both heat-trapping gases and other air pollutants, yielding benefits for human health and fitness. Increased temperatures and changes in precipitation patterns could also increase the vulnerability of Midwest residents to diseases carried by insects and rodents (Ch. 9: Human Health).[58]

ALTERNATIVE TRANSPORTATION OPTIONS CREATE MULTIPLE BENEFITS

The transportation sector produces one-third of U.S. greenhouse gas emissions, and automobile exhaust also contains precursors to fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3), which pose threats to public health. Adopting a low-carbon transportation system with fewer automobiles, therefore, could have immediate health "co-benefits" of both reducing climate change and improving human health via both improved air quality and physical fitness.

Reducing Emissions, Improving Health

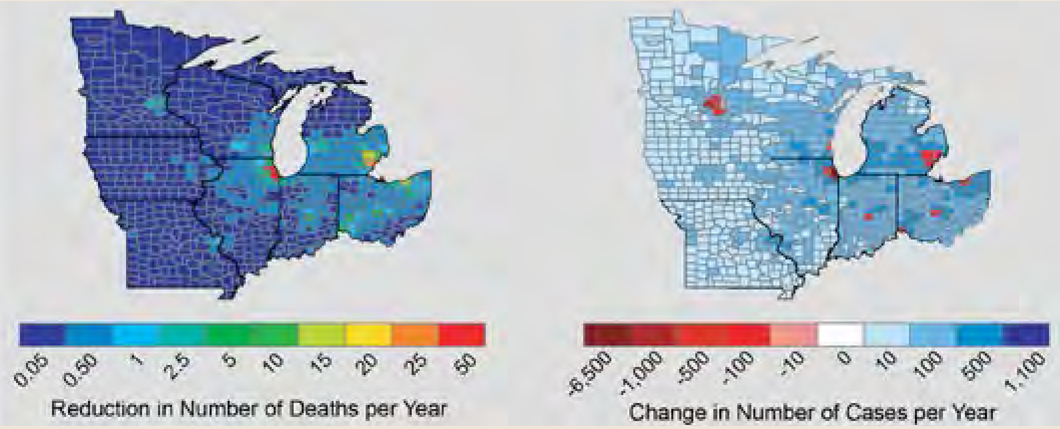

Figure 18.5. Annual reduction in the number of premature deaths (left) and annual change in the number of cases with acute respiratory symptoms (right) due to reductions in particulate matter and ozone caused by reducing automobile exhaust. The maps project health benefits if automobile trips shorter than five miles (round-trip) were eliminated for the 11 largest metropolitan areas in the Midwest. Making 50% of these trips by bicycle just during four summer months would save 1,295 lives and yield savings of more than $8 billion per year from improved air quality, avoided mortality, and reduced health care costs for the upper Midwest alone. (Figure source: Grabow et al. 2012; reproduced with permission from Environmental Health Perspectives[59]).

Key Message 4: Fossil-Fuel Dependent Electricity System

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

The Midwest is a major exporter of electricity to other U.S. regions and has a highly energy-intensive economy (Ch. 10: Energy, Water, and Land, Figure 10.4). Energy use per dollar of gross domestic product is approximately 20% above the national average, and per capita greenhouse gas emissions are 22% higher than the national average due, in part, to the reliance on fossil fuels, particularly coal for electricity generation.[1] A large range in seasonal air temperature causes energy demand for both heating and cooling, with the highest demand for winter heating. The demand for heating in major midwestern cities is typically five to seven times that for cooling,[1] although this is expected to shift as a result of longer summers, more frequent heat waves, and higher humidity, leading to an increase in the number of cooling degree days. This increased demand for cooling by the middle of this century is projected to exceed 10 gigawatts (equivalent to at least five large conventional power plants), requiring more than $6 billion in infrastructure investments.[60] Further, approximately 95% of the electrical generating infrastructure in the Midwest is susceptible to decreased efficiency due to higher temperatures.[60]

Climate change presents the Midwest's energy sector with a number of challenges, in part because of its current reliance on coal-based electricity[1] and an aging, less-reliable electric distribution grid[61] that will require significant reinvestment even without additional adaptations to climate change.[62]

Increased use of natural gas in the Midwest has the potential to reduce emissions of greenhouse gases. The Midwest also has potential to produce energy from zero- and low-carbon sources, given its wind, solar, and biomass resources, and potential for expanded nuclear power. The Midwest does not have the highest solar potential in the country (that is found in the Southwest), but its potential is nonetheless vast, with some parts of the Midwest having as good a solar resource as Florida.[63] More than one-quarter of national installed wind energy capacity, one-third of biodiesel capacity, and more than two-thirds of ethanol production are located in the Midwest (see also Ch. 4: Energy and Ch. 10: Energy, Water, and Land).[1] Progress toward increasing renewable energy is hampered by electricity prices that are distorted through a mix of direct and indirect subsidies and unaccounted-for costs for conventional energy sources.[64]

Key Message 5: Increased Rainfall and Flooding

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Precipitation in the Midwest is greatest in the east, declining towards the west. Precipitation occurs about once every seven days in the western part of the region and once every three days in the southeastern part.[65] The 10 rainiest days can contribute as much as 40% of total precipitation in a given year.[65] Generally, annual precipitation increased during the past century (by up to 20% in some locations), with much of the increase driven by intensification of the heaviest rainfalls.[65,66] This tendency towards more intense precipitation events is projected to continue in the future.[67]

Model projections for precipitation changes are less certain than those for temperature.[3,4] Under a higher emissions scenario (A2), global climate models (GCMs) project average winter and spring precipitation by late this century (2071-2099) to increase 10% to 20% relative to 1971-2000, while changes in summer and fall are not expected to be larger than natural variations. Projected changes in annual precipitation show increases larger than natural variations in the north and smaller in the south (Ch. 2: Our Changing Climate, Key Message 5).[4] Regional climate models (RCMs) using the same emissions scenario also project increased spring precipitation (9% in 2041-2062 relative to 1979-2000) and decreased summer precipitation (by an average of about 8% in 2041-2062 relative to 1979-2000) particularly in the southern portions of the Midwest.[3] Increases in the frequency and intensity of extreme precipitation are projected across the entire region in both GCM and RCM simulations (Figure 18.6), and these increases are generally larger than the projected changes in average precipitation.[3,4]

Flooding can affect the integrity and diversity of aquatic ecosystems. Flooding also causes major human and economic consequences by inundating urban and agricultural land and by disrupting navigation in the region's roads, rivers, and reservoirs (see Ch. 5: Transportation, Ch. 9: Human Health, and Ch. 11: Urban). For example, the 2008 flooding in the Midwest caused 24 deaths, $15 billion in losses via reduced agricultural yields, and closure of key transportation routes.[1] Water infrastructure for flood control, navigation, and other purposes is susceptible to climate change impacts and other forces because the de-

When it Rains, it Pours

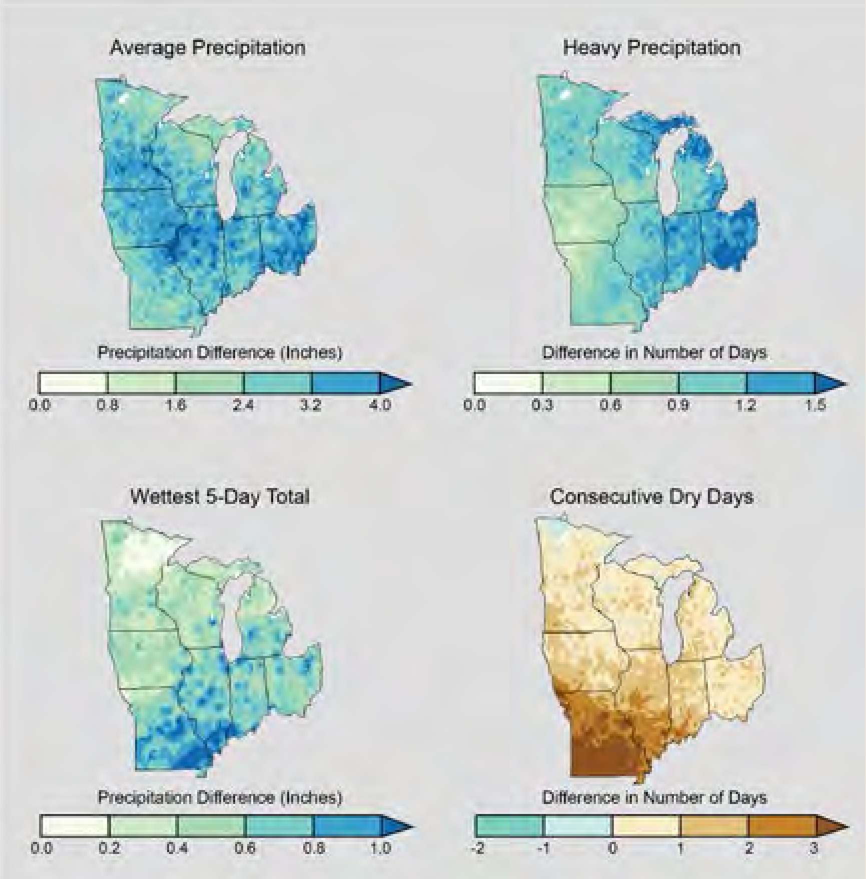

Figure 18.6. Precipitation patterns affect many aspects of life, from agriculture to urban storm drains. These maps show projected changes for the middle of the current century (2041-2070) relative to the end of the last century (1971-2000) across the Midwest under continued emissions (A2 scenario). Top left: the changes in total annual average precipitation. Across the entire Midwest, the total amount of water from rainfall and snowfall is projected to increase. Top right: increase in the number of days with very heavy precipitation (top 2% of all rainfalls each year). Bottom left: increases in the amount of rain falling in the wettest 5-day period over a year. Both (top right and bottom left) indicate that heavy precipitation events will increase in intensity in the future across the Midwest. Bottom right: change in the average maximum number of consecutive days each year with less than 0.01 inches of precipitation. An increase in this variable has been used to indicate an increase in the chance of drought in the future. (Figure source: NOAA NCDC / CICS-NC).

signs are based upon historical patterns of precipitation and streamflow, which are no longer appropriate guides.

Snowfall varies across the region, comprising less than 10% of total precipitation in the south, to more than half in the north, with as much as two inches of water available in the snowpack at the beginning of spring melt in the northern reaches of the river basins.[68] When this amount of snowmelt is combined with heavy rainfall, the resulting flooding can be widespread and catastrophic (see “Cedar Rapids: A Tale of Vulnerability and Response”).[69] Historical observations indicate declines in the frequency of high magnitude snowfall years over much of the Midwest,[70] but an increase in lake effect snowfall.[71] These divergent trends and their inverse relationships with air temperatures make overall projections of regional impacts of the associated snowmelt extremely difficult. Large-scale flooding can also occur due to extreme precipitation in the absence of snowmelt (for example, Rush Creek and the Root River, Minnesota, in August 2007 and multiple rivers in southern Minnesota in September 2010).[72] These warm-season events are projected to increase in magnitude. Such events tend to be more regional and less likely to cover as large an area as those that occur in spring, in part because soil water storage capacity is typically much greater during the summer.

Changing land use and the expansion of urban areas are reducing water infiltration into the soil and increasing surface runoff. These changes exacerbate impacts caused by increased precipitation intensity. Many major Midwest cities are served by combined storm and sewage drainage systems. As surface area has been increasingly converted to impervious surfaces (such as asphalt) and extreme precipitation events have intensified, combined sewer overflow has degraded water quality, a phenomenon expected to continue to worsen with increased urbanization and climate change.[75] The U.S. Environmental Protection Agency (EPA) estimates there are more than 800 billion gallons of untreated combined sewage released into the nation’s waters annually.[76] The Great Lakes, which provide drinking water to more than 40 million people and are home to more than 500 beaches,[75] have been subject to recent sewage overflows. For example, stormwater across the city of Milwaukee recently showed high human fecal pathogen levels at all 45 outflow locations, indicating widespread sewage contamination.[77] One study estimated that increased storm events will lead to an increase of up to 120% in combined sewer overflows into Lake Michigan by 2100 under a very high emissions scenario (A1FI),[75] leading to additional human health issues and beach closures. Municipalities may be forced to invest in new infrastructure to protect human health and water quality in the Great Lakes, and local communities could face tourism losses from fouled nearshore regions.

Increased precipitation intensity also increases erosion, damaging ecosystems and increasing delivery of sediment and subsequent loss of reservoir storage capacity. Increased storm-induced agricultural runoff and rising water temperatures

CEDAR RAPIDS: A TALE OF VULNERABILITY AND RESPONSE

Cedar Rapids, Des Moines, Iowa City, and Ames, Iowa, have all suffered multi-million-dollar losses from floods since 1993. In June 2008, a record flood event exceeded the once-in-500-year flood level by more than 5 feet, causing $5 to $6 billion in damages from flooding, or more than $40,000 per resident of the city of Cedar Rapids.[73] The flood inundated much of the downtown, damaging more than 4,000 structures, including 80% of government offices, and displacing 25,000 people.[74] The record flood at Cedar Rapids was the result of low reservoir capacity and extreme rainfall on soil already saturated from unusually wet conditions. Rainfall amounts comparable to those in 1993 (8 inches over two weeks) overwhelmed a flood control system designed largely for a once-in-100-year flood event. Such events are consistent with observations and projections of wetter springs and more intense precipitation events (see Figure 18.6). With the help of more than $3 billion in funding from the federal and state government, Cedar Rapids is recovering and has taken significant steps to reduce future flood damage, with buyouts of more than 1,000 properties, and numerous buildings adapted with flood protection measures.


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have increased non-point source pollution problems in recent years.[78] This has led to increased phosphorus and nitrogen loading, which in turn is contributing to more and prolonged occurrences of low-oxygen “dead zones” and to harmful, lengthy, and dense algae growth in the Great Lakes and other Midwest water bodies.[79] (Such zones and their causes are also discussed in Ch. 25: Coasts, Ch. 15: Biogeochemical Cycles, and Ch. 3: Water, Key Message 6). Watershed planning can be used to reduce water quantity and quality problems due to changing climate and land use.

While there was no apparent change in drought duration in the Midwest region as a whole over the past century,[80] the average number of days without precipitation is projected to increase in the future. This could lead to agricultural drought and suppressed crop yields.[9] This would also increase thermoelectric power plant cooling water temperatures and decrease cooling efficiency and plant capacity because of the need to avoid discharging excessively warm water (see also Ch. 4: Energy, and Ch. 10: Energy, Water, and Land).[60]

Key Message 6: Increased Risks to the Great Lakes

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

The Great Lakes, North America’s largest freshwater feature, have recently recorded higher water temperatures and less ice cover as a result of changes in regional climate (see also Ch. 2: Our Changing Climate, Key Message 11). Summer surface water temperatures in Lakes Huron increased 5.2°F and in Lake Ontario, 2.7°F, between 1968 and 2002,[81] with smaller increases in Lake Erie.[81,82] Due to the reduction in ice cover, the temperature of surface waters in Lake Superior during the summer increased 4.5°F, twice the rate of increase in air temperature.[83] These lake surface temperatures are projected to rise by as much as 7°F by 2050 and 12.1°F by 2100.[84,85] Higher temperatures, increases in precipitation, and lengthened growing seasons favor production of blue-green and toxic algae that can harm fish, water quality, habitats, and aesthetics,[79,84,86] and could heighten the impact of invasive species already present.[87]

In the Great Lakes, the average annual maximum ice coverage during 2003-2013 was less than 43% compared to the 1962-2013 average of 52%,[88] lower than any other decade during the period of measurements (Figure 18.7), although there is substantial variability from year to year. During the 1970s, which included several extremely cold winters, maximum ice coverage averaged 67%. Less ice, coupled with more frequent and intense storms (as indicated by some analyses of historical wind speeds),[89] leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.[84,90] Reduced ice cover also has the potential to lengthen the shipping season.[91] The navigation season increased by an average of eight days between 1994 and 2011, and the Welland Canal in the St. Lawrence River remained open nearly two weeks longer. Increased shipping days benefit commerce but could also increase shoreline scouring and bring in more invasive species.[91,92]

Changes in lake levels can also influence the amount of cargo that can be carried on ships. On average, a 1000-foot ship sinks into the water by one inch per 270 tons of cargo;[93] thus if a ship is currently limited by water depth, any lowering of lake levels will result in a proportional reduction in the amount of cargo that it can transport to Great Lakes ports. However, current estimates of lake level changes are uncertain, even for continued increases in global greenhouse gas emissions (A2 scenario). The most recent projections suggest a slight decrease or even a small rise in levels.[94] Recent studies have also indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[94,95,96,97] The recent studies, along with the large spread in existing modeling results, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty (see Appendix 3: Climate Science Supplemental Message 8).

Ice Cover in the Great Lakes

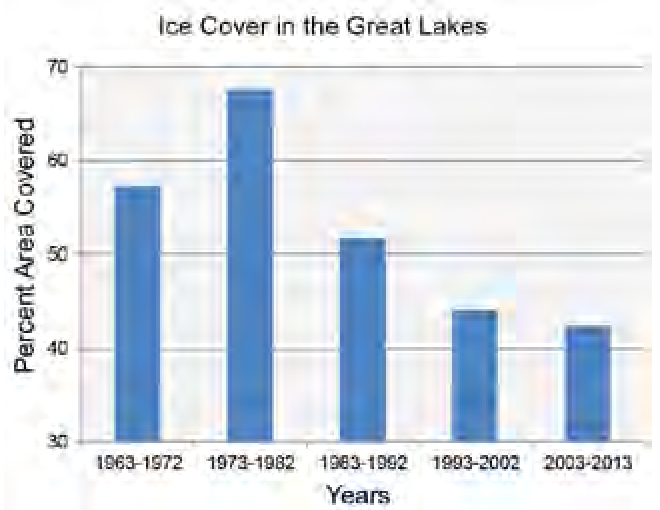

Figure 18.7. Bars show decade averages of annual maximum Great Lakes ice coverage from the winter of 1962-1963, when reliable coverage of the entire Great Lakes began, to the winter of 2012-2013. Bar labels indicate the end year of the winter; for example, 1963-1972 indicates the winter of 1962-1963 through the winter of 1971-1972. The most recent period includes the eleven years from 2003 to 2013. (Data updated from Bai and Wang, 2012[88]).

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PHOTO CREDITS

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

The assessment process for the Midwest Region began with a workshop was that was held July 25, 2011, in Ann Arbor, Michigan. Ten participants discussed the scope and authors for a foundational Technical Input Report (TIR) report entitled "Midwest Technical Input Report."[98] The report, which consisted of nearly 240 pages of text organized into 13 chapters, was assembled by 23 authors representing governmental agencies, non-governmental organizations (NGOs), tribes, and other entities.

The Chapter Author Team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR[98] and of approximately 45 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The Chapter Author Team convened teleconferences and exchanged extensive emails to define the scope of the chapter for their expert deliberation of input materials and to generate the chapter text and figures. Each expert drafted key messages, initial text and figure drafts and traceable accounts that pertained to their individual fields of expertise. These materials were then extensively discussed by the team and were approved by the team members.

KEY MESSAGE #1 TRACEABLE ACCOUNT

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for altered growing seasons across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] and its references provide specific details for the Midwest. Evidence for longer growing seasons in the Midwest is based on regional temperature records and is incontrovertible, as is evidence for increasing carbon dioxide concentrations.

U.S. Department of Agriculture data tables provide evidence for the importance of the eight Midwest states for U.S. agricultural production.[8] Evidence for the effect of future elevated carbon dioxide concentrations on crop yields is based on scores of greenhouse and field experiments that show a strong fertilization response for C_3 plants such as soybeans and wheat and a positive but not as strong a response for C_4 plants such as corn. Observational data, evidence from field experiments, and quantitative modeling are the evidence base of the negative effects of extreme weather events on crop yield: early spring heat waves followed by normal frost events have been shown to decimate Midwest fruit crops; heat waves during flowering, pollination, and grain filling have been shown to significantly reduce corn and wheat yields; more variable and intense spring rainfall has delayed spring planting in some years and can be expected to increase erosion and runoff; and floods have led to crop losses.[12,13,14]

New information and remaining uncertainties

Key issues (uncertainties) are: a) the rate at which grain yield improvements will continue to occur, which could help to offset the overall negative effect of extreme events at least for grain crops (though not for individual farmers); and b) the degree to which genetic improvements could make some future crops more tolerant of extreme events such as drought and heat stress. Additional uncertainties are: c) the degree to which accelerated soil carbon loss will occur as a result of warmer winters and the resulting effects on soil fertility and soil water availability; and d) the potential for increased pest and disease pressure as southern pests such as soybean rust move northward and existing pests better survive milder Midwest winters.

Assessment of confidence based on evidence

Because nearly all studies published to date in the peer-reviewed literature agree that Midwest crops benefit from CO_2 fertilization and some benefit from a longer growing season, there is **very high** confidence in this component of the key message.

Studies also agree that full benefits of climate change will be offset partly or fully by more frequent heat waves, early spring thaws followed by freezing temperatures, more variable and intense rainfall events, and floods. Again, there is **very high** confidence in this aspect.

There is less certainty (**high**) about pest effects and about the potential for adaptation actions to significantly mitigate the risk of crop loss.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key Message #2 Traceable Account

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for increased temperatures and altered growing seasons across the U.S. is discussed in Chapter 2 (Our Changing Climate, Key Messages 3 and 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment,"[4] with its references, provides specific details for the Midwest. Evidence that species have been shifting northward or ascending in altitude has been mounting for numerous species, though less so for long-lived trees. Nearly all studies to date published in the peer-reviewed literature agree that many of the boreal species of the north will eventually retreat northward. The question is when. Multiple models and paleoecological evidence show these trends have occurred in the past and are projected to continue in the future.[36]

The forests of the eastern United States (including the Midwest) have been accumulating large quantities of carbon over the past century,[23] but evidence shows this trend is slowing in recent decades. There is a large amount of forest inventory data supporting the gradual decline in carbon accumulation throughout the eastern United States,[99] as well as evidence of increasing disturbances and disturbance agents that are reducing overall net productivity in many of the forests.

New information and remaining uncertainties

A key issue (uncertainty) is the rate of change of habitats and for organisms adapting or moving as habitats move. The key questions are: How much will the habitats change (what scenarios and model predictions will be most correct)? As primary habitats move north, which species will be able to keep up with changing habitats on their own or with human intervention through assisted migration, management of migration corridors, or construction or maintenance of protected habitats within species' current landscapes?

Viable avenues to improving the information base are determining which climate models exhibit the best ability to reproduce the historical and potential future change in habitats, and determining how, how fast, and how far various species can move or adapt.

An additional key source of uncertainty is whether projected disturbances to forests are chronic or episodic in nature.[45]

Assessment of confidence based on evidence

There is **very high** confidence in this key message, given the evidence base and remaining uncertainties.

Key Message #3 Traceable Account

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather such as heat waves across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 7) and its Traceable Accounts. Specific details for the Midwest are in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Heat waves: The occurrence of heat waves in the recent past has been well-documented,[1,15,49] as have health outcomes (particularly with regards to mortality). Projections of thermal regimes indicate increased frequency of periods with high air temperatures (and high apparent temperatures, which are a function of both air temperature and humidity). These projections are relatively robust and consistent between studies.

Humidity: Evidence on observed and projected increased humidity can be found in a recent study.[49]

Air quality: In 2008, in the region containing North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio, over 26 million people lived in counties that failed the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ (particles with diameter below 2.5 microns), and over 24 million lived in counties that failed the NAAQS for ozone (O_3).[1] Because not all counties have air quality measurement stations in place, these data must be considered a lower bound on the actual number of counties that violate the NAAQS. Given that the NAAQS were designed principally with the goal of protecting human health, failure to meet these standards implies a significant fraction of the population live in counties characterized by air quality that is harmful to human health. While only relatively few studies have sought to make detailed air quality projections for the future, those that have[1] generally indicate declining air quality (see uncertainties below).

Water quality: The EPA estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually.[76] Combined sewers are designed to capture both sanitary sewage and stormwater. Combined sewer overflows lead to discharge of untreated sewage as a result of precipitation events, and can threaten human health. While not all urban areas within the Midwest have combined sewers for delivery to wastewater treatment plants, many do (for example, Chicago and Milwaukee), and such systems are vulnerable to combined sewer overflows during extreme precipitation events. Given projected increases in the frequency and intensity of extreme precipitation events in the Midwest (Chapter 2: Our Changing Climate, Key Message 6),[75] it appears that sewer overflow will continue to constitute a significant current health threat and a critical source of climate change vulnerability for major urban areas within the Midwest.

New information and remaining uncertainties

Key issues (uncertainties) are: Human health outcomes are contingent on a large number of non-climate variables. For example, morbidity and mortality outcomes of extreme heat are strongly determined by a) housing stock and access to air-conditioning in residences; b) existence and efficacy of heat wave warning and response plans (for example, foreign-language-appropriate communications and transit plans to public cooling centers, especially for the elderly); and c) co-stressors (for example, air pollution). Further, heat stress is dictated by apparent temperature, which is a function of both air temperature and humidity. Urban heat islands tend to exacerbate elevated temperatures and are largely determined by urban land use and human-caused heat emissions. Urban heat island reduction plans (for example, planted green roofs) represent one ongoing intervention. Nevertheless, the occurrence of extreme heat indices will increase under all climate scenarios. Thus, in the absence of policies to reduce heat-related illness/death, these impacts will increase in the future.

Air quality is a complex function not only of physical meteorology but emissions of air pollutants and precursor species. However, since most chemical reactions are enhanced by warmer temperatures, as are many air pollutant emissions, warmer temperatures may lead to worsening of air quality, particularly with respect to tropospheric ozone (see Ch. 9: Human Health). Changes in humidity are more difficult to project but may amplify the increase in heat stress due to rising temperatures alone.[49]

Combined sewer overflow is a major threat to water quality in some midwestern cities now. The tendency towards increased magnitude of extreme rain events (documented in the historical record and projected to continue in downscaling analyses) will cause an increased risk of waterborne disease outbreaks in the absence of infrastructure overhaul. However, mitigation actions are available, and the changing structure of cities (for example, reducing impervious surfaces) may offset the impact of the changing climate.

Assessment of confidence based on evidence

In the absence of concerted efforts to reduce the threats posed by heat waves, increased humidity, degraded air quality and degraded water quality, climate change will increase the health risks associated with these phenomena. However, these projections are contingent on underlying assumptions regarding socioeconomic conditions and demographic trends in the region. Confidence is therefore **high** regarding this key message.

Key Message #4 Traceable Account

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The Midwest's disproportionately large reliance on coal for electricity generation and the energy intensity of its agricultural and manufacturing sectors are all well documented in both government and industry records, as is the Midwest's contribution to greenhouse gases.[1] The region's potential for zero- and lower-carbon energy production is also well documented by government and private assessments. Official and regular reporting by state agencies and non-governmental organizations demonstrates the Midwest's progress toward a decarbonized energy mix (Ch. 4: Energy; Ch. 10: Energy, Water, and Land).[1]

There is evidence that the Midwest is steadily decarbonizing its electricity generation through a combination of new state-level policies (for example, energy efficiency and renewable energy standards) and will continue to do so in response to low natural gas prices, falling prices for renewable electricity (for example, wind and solar), greater market demand for lower-carbon energy from consumers, and new EPA regulations governing new power plants. Several midwestern states have established Renewable Portfolio Standards (see https://www.misoenergy.org/WhatWeDo/StrategicInitiatives/Pages/RenewablePortfolioStandards.aspx).

New information and remaining uncertainties

There are four key uncertainties. The first uncertainty is the net effect of emerging EPA regulations on the future energy mix of the Midwest. Assessments to date suggest a significant number of coal plants will be closed or repowered with lower-carbon natural gas; and even coal plants that are currently thought of as "must run" (to maintain the electric grid's reliability) may be able to be replaced in some circumstances with the right combination of energy efficiency, new transmission lines, demand response, and distributed generation. A second key uncertainty is whether or not natural gas prices will remain at their historically low levels. Given that there are really only five options for meeting electricity demand – energy efficiency, renewables, coal, nuclear, and natural gas – the replacement of coal with natural gas for electricity production would have a significant impact on greenhouse gas emissions in the region. Third is the uncertain future for federal policies that have spurred renewable energy development to date, such as the Production Tax Credit for wind. While prices for both wind and solar continue to fall, the potential loss of tax credits may dampen additional market penetration of these technologies. A fourth uncertainty is the net effect of climate change on energy demand, and the cost of meeting that new demand profile. Research to date suggests the potential for a significant swing from the historically larger demand for heating in the winter to more demand in the summer instead, due to a warmer, more humid climate.[3]

Assessment of confidence based on evidence

There is no dispute about the energy intensity of the midwestern economy, nor its disproportionately large contribution of greenhouse gas emissions. Similarly, there is broad agreement about the Midwest's potential for—and progress toward—lower-carbon electricity production. There is therefore **very high** confidence in this statement.

Key Message #5 Traceable Account

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather and increased precipitation across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Messages 5, 6, and 7) and its Traceable Accounts. Specific details for the Midwest are detailed in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

There is compelling evidence that annual total precipitation has been increasing in the region, with wetter winters and springs, drier summers, an increase in extreme precipitation events, and changes in snowfall patterns. These observations are consistent with climate model projections. Both the observed trends and climate models suggest these trends will increase in the future.

Recent records also indicate evidence of a number of high-impact flood events in the region. Heavy precipitation events cause increased kinetic energy of surface water and thus increase erosion. Heavy precipitation events in the historical records have been shown to be associated with discharge of partially or completely untreated sewage due to the volumes of water overwhelming combined sewer systems that are designed to capture both domestic sewage and stormwater.

Climate downscaling projections tend to indicate an increase in the frequency and duration of extreme events (both heavy precipitation and meteorological drought) in the future.

An extensive literature survey and synthetic analysis is presented in chapters in a recent book[100] for impacts on water quality, transportation, agriculture, health, and infrastructure.

New information and remaining uncertainties

Precipitation is much less readily measured or modeled than air temperature.[3] Thus both historical tendencies and projections for precipitation are inherently less certain than for temperature. Most regional climate models still have a positive bias in precipitation frequency but a negative bias in terms of precipitation amount in extreme events.

Flood records are very heterogeneous and there is some ambiguity about the degree to which flooding is a result of atmospheric conditions.[69] Flooding is not solely the result of incident precipitation but is also a complex function of the preceding conditions such as soil moisture content and extent of landscape infiltration. A key issue (uncertainty) is the future distribution of snowfall. Records indicate that snowfall is decreasing in the southern parts of the region, along with increasing lake effect snow. Climate models predict these trends will increase. There is insufficient knowledge about how this change in snowfall patterns will affect flooding and associated problems, but it is projected to affect the very large spring floods that typically cause the worst flooding in the region. In addition, recent data and climate predictions indicate drier summer conditions, which could tend to offset the effects of higher intensity summer storms by providing increased water storage in the soils. The relative effects of these offsetting trends need to be assessed. To determine future flooding risks, hydrologic modeling is needed that includes the effects of the increase in extreme events, changing snow patterns, and shifts in rainfall patterns. Adaptation measures to reduce soil erosion and combined sewer overflow (CSO) events are available and could be widely adopted.

The impacts of increased magnitude of heavy precipitation events on water quality, agriculture, human health, transportation, and infrastructure will be strongly determined by the degree to which the resilience of such systems is enhanced (for example, some cities are already implementing enhanced water removal systems).

Assessment of confidence based on evidence

There have been improvements in agreement between observed precipitation patterns and model simulations. Also an increase in extreme precipitation events is consistent with first-order reasoning and increased atmospheric water burdens due to increased air temperature. Recent data suggest an increase in flooding in the region but there is uncertainty about how changing snow patterns will affect flood events in the future. Thus there is **high** confidence in increases in high-magnitude rainfall events and extreme precipitation events, and that these trends are expected to continue. There is **medium** confidence that, in the absence of substantial adaptation actions, the enhancement in extreme precipitation and other tendencies in land use and land cover result in a projected increase in flooding. There is **medium** confidence that, in the absence of major adaptation actions, the enhancement in extreme precipitation will tend to increase the risk of erosion, declines in water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.[3]

Key Message #6 Traceable Account

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for changes in ice cover due to increased temperatures across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 11) and its Traceable Accounts. Specific details for the Midwest are detailed in “Climate Trends and Scenarios for the U.S. National Climate Assessment”[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Altered fish communities: Warmer lakes and streams will certainly provide more habitat for warmwater species as conditions in northern reaches of the basin become more suitable for warmwater fish and as lakes and streams are vacated by cool- and coldwater species.[84] Habitat for coldwater fish, though not expected to disappear, will shrink substantially, though it could also expand in some areas, such as Lake Superior. Whether climate change expands the range of any type of fish is dependent on the availability of forage fish, as higher temperatures also necessitate greater food intake.

Increased abundances of invasive species: As climate change alters water temperatures, habitat, and fish communities, conditions that once were barriers to alien species become conduits for establishment and spread.[84] This migration will alter drastically the fish communities of the Great Lakes basin. Climate change is also projected to heighten the impact of invasive species already present in the Great Lakes basin. Warmer winter conditions, for instance, have the potential to benefit alewife, round gobies, ruffe, sea lamprey, rainbow smelt, and other non-native species. These species have spread rapidly throughout the basin and have already inflicted significant ecological and economic harm.

Declining beach health and harmful algal blooms: Extreme events increase runoff, adding sediments, pollutants, and nutrients to the Great Lakes. The Midwest has experienced rising trends in precipitation and runoff. Agricultural runoff, in combination with increased water temperatures, has caused considerable non-point source pollution problems in recent years, with increased phosphorus and nitrogen loadings from farms contributing to more frequent and prolonged occurrences of anoxic "dead zones" and harmful, dense algae growth for long periods. Stormwater runoff that overloads urban sewer systems during extreme events adds to increased levels of toxic substances, sewage, and bacteria in the Great Lakes, affecting water quality, beach health, and human well-being. Increased storm events caused by climate change will lead to an increase in combined sewer overflows.[84]

Decreased ice cover: Increasingly mild winters have shortened the time between when a lake freezes and when it thaws.[101] Scientists have documented a relatively constant decrease in Great Lakes ice cover since the 1970s, particularly for Lakes Superior, Michigan, Huron, and Ontario. The loss of ice cover on the Great Lakes has both ecological and economic implications. Ice serves to protect shorelines and habitat from storms and wave power. Less ice—coupled with more frequent and intense storms—leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.

Water levels: The 2009 NCA[102] included predictions of a significant drop in Great Lakes levels by the end of the century, based on methods of linking climate models to hydrologic models. These methods have been significantly improved by fully coupling the hydrologic cycle among land, lake, and atmosphere.[97] Without accounting for that cycle of interactions, a study[96] concluded that increases in precipitation would be negated by increases in winter evaporation from less ice cover and by increases in summer evaporation and evapotranspiration from warmer air temperatures, under a scenario of continued increases in global emissions (SRES A2 scenario). Declines of 8 inches to 2 feet have been projected by the end of this century, depending on the specific lake in question.[96] A recent comprehensive assessment,[94] however, has concluded that with a continuation of current rising emissions trends (A2), the lakes will experience a slight decrease or even a rise in water levels; the difference from earlier studies is because earlier studies tended to overstress the amount of evapotranspiration expected to occur. The range of potential future lake levels remains large and includes the earlier projected decline. Overall, however, scientists project an increase in precipitation in the Great Lakes region (with extreme events projected to contribute to this increase), which will contribute to maintenance of or an increase in Great Lakes water levels. However, water level changes are not predicted to be uniform throughout the basin.

Shipping: Ice cover is expected to decrease dramatically by the end of the century, possibly lengthening the shipping season and, thus, facilitating more shipping activity. Current science suggests water levels in the Great Lakes are projected to fall slightly or might even rise over the short run. However, by causing even a small drop in water levels, climate change could make the costs of shipping increase substantially. For instance, for every inch of draft a 1000-foot ship gives up, its capacity is reduced by 270 tons.[93] Lightened loads today already add about $200,000 in costs to each voyage.

New information and remaining uncertainties

Key issues (uncertainties) are: Water levels are influenced by the amount of evaporation from decreased ice cover and warmer air temperatures, by evapotranspiration from warmer air temperatures, and by potential increases in inflow from more precipitation. Uncertainties about Great Lakes water levels are high, though most models suggest that the decrease in ice cover will lead to slightly lower water levels, beyond natural fluctuations.

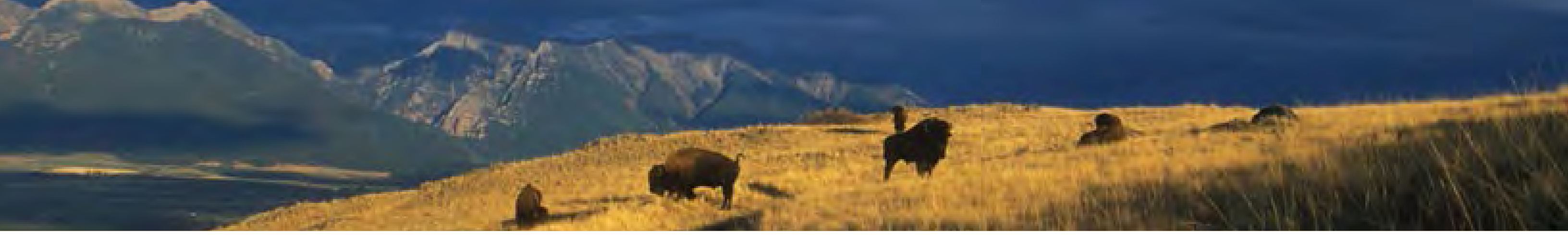
The spread of invasive species into the system is near-certain (given the rate of introductions over the previous 50 years) without major policy and regulatory changes. However, the changes in Great Lakes fish communities are based on extrapolation from known fishery responses to projected responses to expected changing conditions in the basin. Moreover, many variables beyond water temperature and condition affect fisheries, not the least of which is the availability of forage fish. Higher water temperatures necessitate greater food intake, yet the forage base is changing rapidly in many parts of the Great Lakes basin, thus making the projected impact of climate change on fisheries difficult to discern with very high certainty.

Assessment of confidence based on evidence

Peer-reviewed literature about the effects of climate change are in broad agreement that air and surface water temperatures are rising and will continue to do so, that ice cover is declining steadily, and that precipitation and extreme events are on the rise. For large lake ecosystems, these changes have well-documented effects, such as effects on algal production, stratification (change in water temperature with depth), beach health, and fisheries. Key uncertainties exist about Great Lakes water levels and the impact of climate change on fisheries.

A qualitative summary of climate stressors and coastal margin vulnerabilities for the Great Lakes is given in a technical input report.[84] We have high confidence that the sum of these stressors will exceed the risk posed by any individual stressor. However, quantifying the cumulative impacts of those stressors is very challenging.

Given the evidence and remaining uncertainties, there is **very high** confidence in this key message, except **high** confidence for lake levels changing, and **high** confidence that declines in ice cover will continue to lengthen the commercial navigation season. There is limited information regarding exactly how invasive species may respond to changes in the regional climate, resulting in **medium** confidence for that part of the key message.



Climate Change Impacts in the United States

CHAPTER 19
GREAT PLAINS

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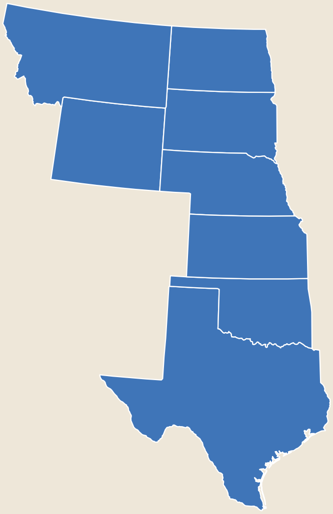

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On the Web: http://nca2014.globalchange.gov/report/regions/great-plains

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

19 GREAT PLAINS

Key Messages

1. **Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.**
2. **Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices.**
3. **Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.**
4. **Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.**
5. **The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.**

The Great Plains is a diverse region where climate and water are woven into the fabric of life. Day-to-day, month-to-month, and year-to-year changes in the weather can be dramatic and challenging for communities and their commerce. The region experiences multiple climate and weather hazards, including floods, droughts, severe storms, tornadoes, hurricanes, and winter storms. In much of the Great Plains, too little precipitation falls to replace that needed by humans, plants, and animals. These variable conditions in the Great Plains already stress communities and cause billions of dollars in damage; climate change will add to both stress and costs.

The people of the Great Plains historically have adapted to this challenging climate. Although projections suggest more frequent and more intense droughts, severe rainfall events, and heat waves, communities and individuals can reduce vulnerabilities through the use of new technologies, community-driven policies, and the judicious use of resources. Adaptation (means of coping with changed conditions) and mitigation (reducing emissions of heat-trapping gases to reduce the speed and amount of climate change) choices can be locally driven, cost effective, and beneficial for local economies and ecosystem services.


USFWS

Temperature and Precipitation Distribution in the Great Plains

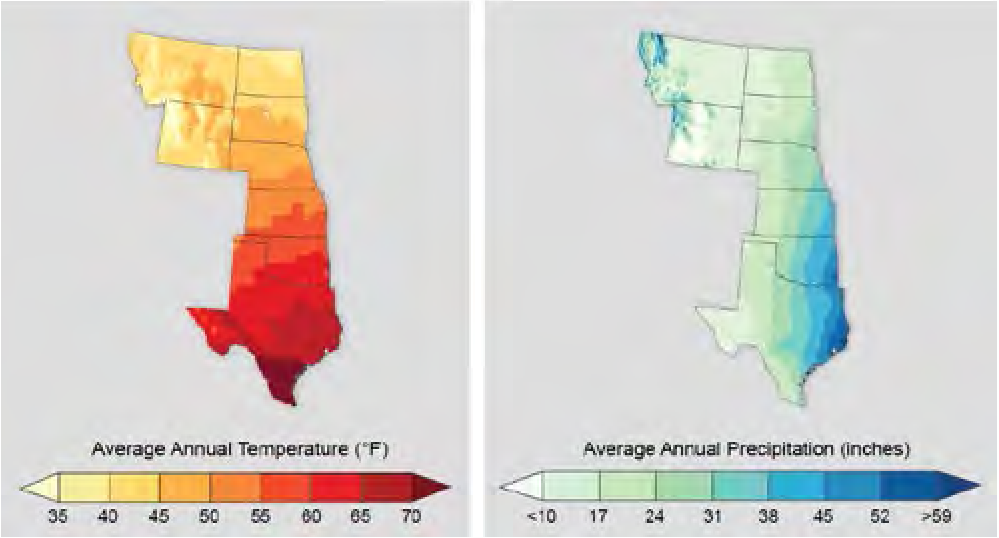


Figure 19.1. The region has a distinct north-south gradient in average temperature patterns (left), with a hotter south and colder north. For precipitation (right), the regional gradient runs west-east, with a wetter east and a much drier west. Averages shown here are for the period 1981-2010. (Figure source: adapted from Kunkel et al. 2013[4]).

Significant climate-related challenges are expected to involve 1) resolving increasing competition among land, water, and energy resources; 2) developing and maintaining sustainable agricultural systems; 3) conserving vibrant and diverse ecological systems; and 4) enhancing the resilience of the region's people to the impacts of climate extremes. These growing challenges will unfold against a changing backdrop that includes a growing urban population and declining rural population, new economic factors that drive incentives for crop and energy production, advances in technology, and shifting policies such as those related to farm and energy subsidies.

The Great Plains region features relatively flat plains that increase in elevation from sea level to more than 5,000 feet at the base of mountain ranges along the Continental Divide. Forested mountains cover western Montana and Wyoming, extensive rangelands spread throughout the Plains, marshes extend along Texas' Gulf Coast, and desert landscapes distinguish far west Texas.[1] A highly diverse climate results from the region's large north-south extent and change of elevation. This regional diversity also means that climate change impacts will vary across the region.

Great Plains residents already must contend with weather challenges from winter storms, extreme heat and cold, severe thunderstorms, drought, and flood-producing rainfall. Texas' Gulf Coast averages about three tropical storms or hurricanes every four years,[2] generating coastal storm surge and sometimes bringing heavy rainfall and damaging winds hundreds of miles inland. The expected rise in sea level will result in the potential for greater damage from storm surge along the Gulf Coast of Texas (see Ch. 25: Coasts).

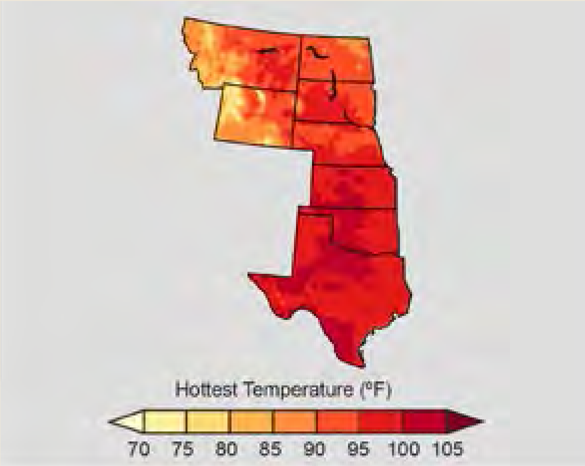
Annual average temperatures range from less than 40°F in the mountains of Wyoming and Montana to more than 70°F in South Texas, with extremes ranging from -70°F in Montana to 121°F in North Dakota and Kansas.[3] Summers are long and hot in the south; winters are long and often severe in the north. North Dakota's increase in annual temperature over the past 130 years is the fastest in the contiguous U.S. and is mainly driven by warming winters.[4]

The region has a distinct north-south gradient in average temperature patterns, with a hotter south and colder north (Figure 19.1). Average annual precipitation greater than 50 inches supports lush vegetation in eastern Texas and Oklahoma. For most places, however, average rainfall is less than 30 inches, with some of Montana, Wyoming, and far west Texas receiving less than 15 inches a year. Across much of the region, annual water loss from transpiration by plants and from evaporation is higher than annual precipitation, making these areas particularly susceptible to droughts.

Projected climate change

For an average of seven days per year, maximum temperatures reach more than 100°F in the Southern Plains and about 95°F in the Northern Plains (Figure 19.2). These high temperatures are projected to occur much more frequently, even under a scenario of substantial reductions in heat-trapping gas (also called greenhouse gas) emissions (B1), with days over 100°F projected to double in number in the north and quadruple in the south by mid-century (Ch. 2: Our Changing Climate, Key Message 7).[4] Similar increases are expected in the number of nights with minimum temperatures higher than 80°F in the south and 60°F in the north (cooler in mountain regions; see Figure 19.3). These increases in extreme heat will have many negative consequences, including increases in surface water losses, heat stress, and demand for air conditioning.[5] These negative consequences will more than offset the benefits of warmer winters, such as lower winter heating demand, less cold stress on humans and animals, and a longer growing season, which will be extended by mid-century an average of 24 days relative to the 1971-2000 average.[4,5] More overwintering insect populations are also expected.[5]

Historical Temperature on the 7 Hottest Days of the Year



The historical (1971-2000) distribution of temperature for the hottest 2% of days (about seven days a year) echoes the distinct north-south gradient in average temperatures.

Projected Change in Number of Hot Days

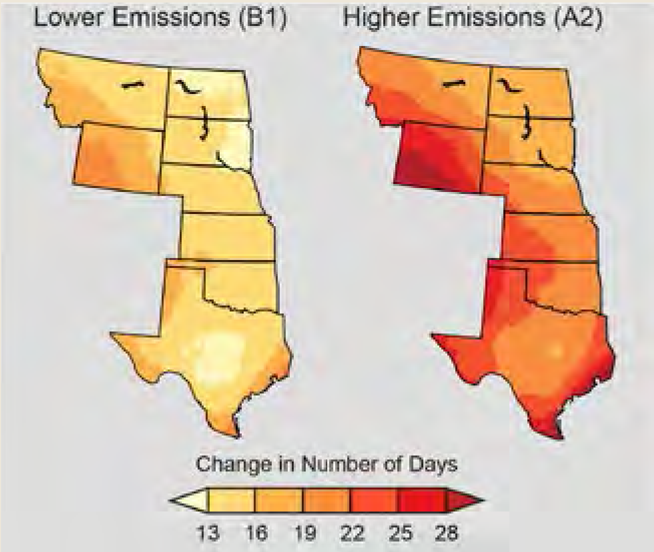
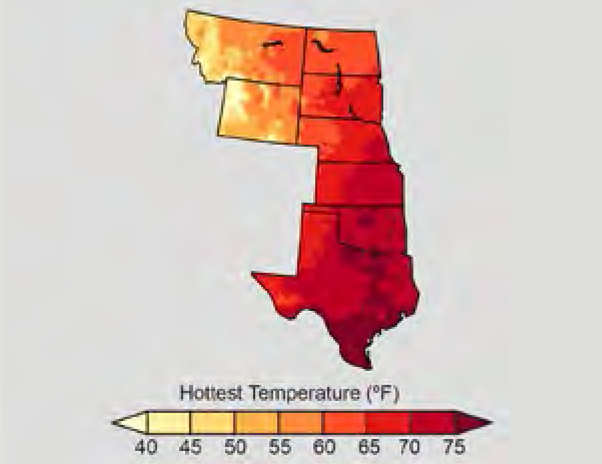


Figure 19.2. The number of days with the hottest temperatures is projected to increase dramatically. By mid-century (2041-2070), the projected change in the number of days exceeding those hottest temperatures is greatest in the western areas and Gulf Coast for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).

Historical Temperature on the 7 Warmest Nights of the Year



The historical (1971-2000) distribution of temperature for the warmest 2% of nights (about seven days a year) echoes the distinct north-south gradient in average temperatures.

Projected Change in Number of Warm Nights

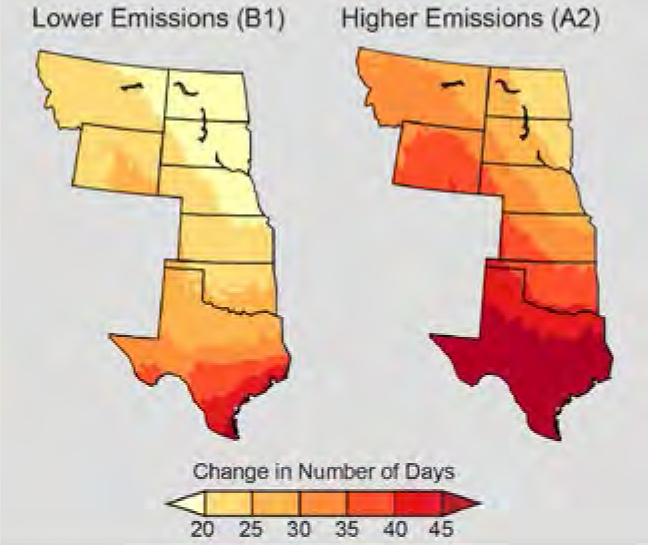
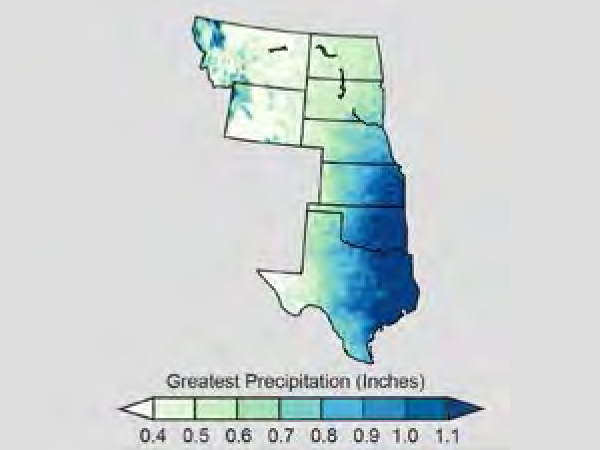


Figure 19.3. The number of nights with the warmest temperatures is projected to increase dramatically. By mid-century (2041-2070), the projected change in number of nights exceeding those warmest temperatures is greatest in the south for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).

Winter and spring precipitation is projected to increase in the northern states of the Great Plains region under the A2 scenario, relative to the 1971-2000 average. In central areas, changes are projected to be small relative to natural variations (Ch. 2: Our Changing Climate, Key Message 5).[4] Projected changes in summer and fall precipitation are small except for summer drying in the central Great Plains, although the exact locations of this drying are uncertain. The number of days with heavy precipitation is expected to increase by mid-century, especially in the north (Ch. 2: Our Changing Climate, Key Message 6). Large parts of Texas and Oklahoma are projected to see longer dry spells (up to 5 more days on average by mid-century). By contrast, changes are projected to be minimal in the north (Ch. 2: Our Changing Climate, Key Message 7).[4]

Historical Amount of Precipitation on the 7 Wettest Days of the Year



The historical (1971-2000) distribution of the greatest 2% of daily precipitation (about seven days a year) echoes the regional west-east gradient in average precipitation.

Projected Change in Number of Heavy Precipitation Days

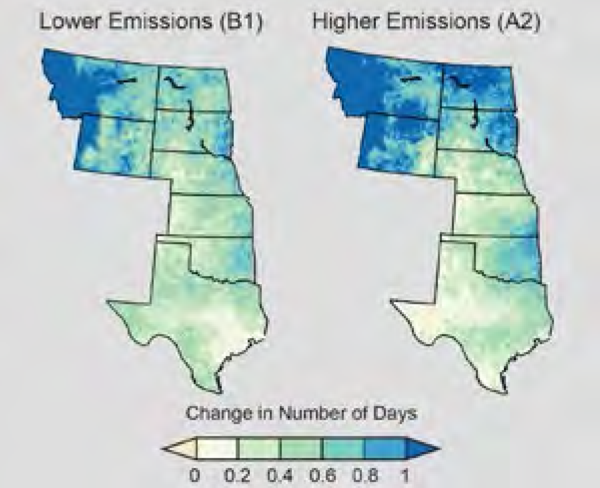


Figure 19.4. The number of days with the heaviest precipitation is not projected to change dramatically. By mid-century (2041-2070), the projected change in days exceeding those precipitation amounts remains greatest in the northern area for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).

Projected Change in Number of Consecutive Dry Days

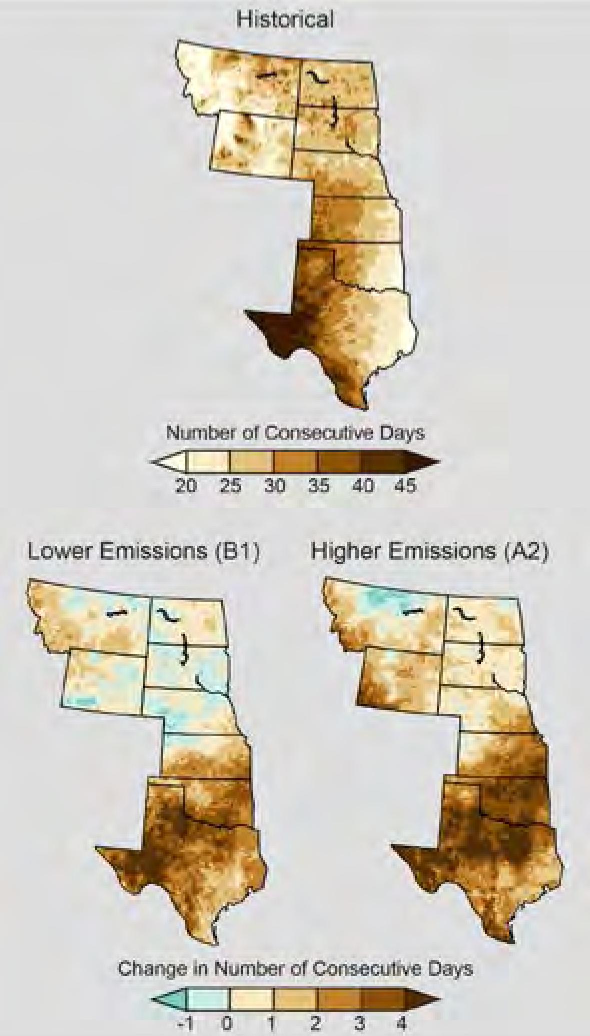


Figure 19.5. Current regional trends of a drier south and a wetter north are projected to become more pronounced by mid-century (2041-2070 as compared to 1971-2000 averages). Maps show the maximum annual number of consecutive days in which limited (less than 0.01 inches) precipitation was recorded on average from 1971 to 2000 (top), projected changes in the number of consecutive dry days assuming substantial reductions in emissions (B1), and projected changes if emissions continue to rise (A2). The southeastern Great Plains, which is the wettest portion of the region, is projected to experience large increases in the number of consecutive dry days. (Figure source: NOAA NCDC / CICS-NC).

Key Message 1: Energy, Water and Land Use

Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.

Energy, water, and land use are inherently interconnected,[6] and climate change is creating a new set of challenges for these critical sectors (Ch. 2: Our Changing Climate; Ch. 10: Energy, Water, and Land).[7,8,9] The Great Plains is rich with energy resources, primarily from coal, oil, and natural gas, with growing wind and biofuel industries.[10] Texas produces 16% of U.S. energy (mostly from crude oil and natural gas), and Wyoming provides an additional 14% (mostly from coal). North Dakota is the second largest producer of oil in the Great Plains, behind Texas. Nebraska and South Dakota rank third and fifth in biofuel production, and five of the eight Great Plains states have more than 1,000 megawatts of installed wind generation capacity, with Texas topping the list.[11] More than 80% of the region's land area is used for agriculture, primarily cropland, pastures, and rangeland. Other land uses include forests, urban and rural development, transportation, conservation, and industry.

Significant amounts of water are used to produce energy[7,12] and to cool power plants.[13] Electricity is consumed to collect, purify, and pump water. Although hydraulic fracturing to release oil and natural gas is a small component of total water use,[14] it can be a significant proportion of water use in local and rural groundwater systems. Energy facilities, transmission lines, and wind turbines can fragment both natural habitats and agriculture lands (Ch. 10: Energy, Water, and Land).[5]

The trend toward more dry days and higher temperatures across the south will increase evaporation, decrease water supplies, reduce electricity transmission capacity, and increase cooling demands. These changes will add stress to limited water resources and affect management choices related to irrigation, municipal use, and energy generation.[15] In the Northern Plains, warmer winters may lead to reduced heating demand while hotter summers will increase demand for air conditioning, with the summer increase in demand outweighing the winter decrease (Ch. 4: Energy, Key Message 2).[15]

Changing extremes in precipitation are projected across all seasons, including higher likelihoods of both increasing heavy rain and snow events[4] and more intense droughts (Ch. 2: Our Changing Climate, Key Messages 5 and 6).[16] Winter and spring precipitation and very heavy precipitation events are both projected to increase in the northern portions of the area, leading to increased runoff and flooding that will reduce water quality and erode soils. Increased snowfall, rapid spring warming, and intense rainfall can combine to produce devastating floods, as is already common along the Red River of the North. More intense rains will also contribute to urban flooding.

Increased drought frequency and intensity can turn marginal lands into deserts. Reduced per capita water storage will continue to increase vulnerability to water shortages.[17] Federal and state legal requirements mandating water allocations for ecosystems and endangered species add further competition for water resources.

Diminishing water supplies and rapid population growth are critical issues in Texas. Because reservoirs are limited and have high evaporation rates, San Antonio has turned to the Edwards Aquifer as a major source of groundwater storage. Nineteen water districts joined to form a Regional Water Alliance for sustainable water development through 2060. The alliance creates a competitive market for buying and selling water rights and simplifies transfer of water rights.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Key Message 2: Sustaining Agriculture

Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices

The important agricultural sector in the Great Plains, with a total market value of about $92 billion (the most important being crops at 43% and livestock at 46%),[18] already contends with significant climate variability (Ch. 6: Agriculture). Projected changes in climate, and human responses to it, will affect aspects of the region's agriculture, from the many crops that rely solely on rainfall, to the water and land required for increased energy production from plants, such as fuels made from corn or switchgrass (see Ch. 10: Energy, Water, and Land).

Water is central to the region's productivity. The High Plains Aquifer, including the Ogallala, is a primary source for irrigation.[19] In the Northern Plains, rain recharges this aquifer quickly, but little recharge occurs in the Southern Plains.[20,21]

Projected changes in precipitation and temperature have both positive and negative consequences to agricultural productivity in the Northern Plains. Projected increases in winter and spring precipitation in the Northern Plains will benefit agricultural productivity by increasing water availability through soil moisture reserves during the early growing season, but this can be offset by fields too wet to plant. Rising temperatures will lengthen the growing season, possibly allowing a second annual crop in some places and some years. Warmer winters pose challenges.[22,23,24] For example, some pests and invasive weeds will be able to survive the warmer winters.[25] Winter crops that leave dormancy earlier are susceptible to spring freezes.[26] Rainfall events already have become more intense,[27] increasing erosion and nutrient runoff, and projections are that the frequency and severity of these heavy rainfall events will increase.[4,28] The Northern Plains will remain vulnerable to periodic drought because much of the projected increase in precipitation is expected to occur in the cooler months while increasing temperatures will result in additional evapotranspiration.

In the Central and Southern Plains, projected declines in precipitation in the south and greater evaporation everywhere due to higher temperatures will increase irrigation demand and exacerbate current stresses on agricultural productivity. Increased water withdrawals from the Ogallala Aquifer and High Plains Aquifer would accelerate ongoing depletion in the southern parts of the aquifers and limit the ability to irrigate.[21,29] Holding other aspects of production constant, the climate impacts of shifting from irrigated to dryland agriculture would reduce crop yields by about a factor of two.[30] Under these climate-induced changes, adaptation of agricultural practices will be needed, however, there may be constraints on social-ecological adaptive capacity to make these adjustments (see also Ch. 28: Adaptation).

Increases in Irrigated Farmland in the Great Plains

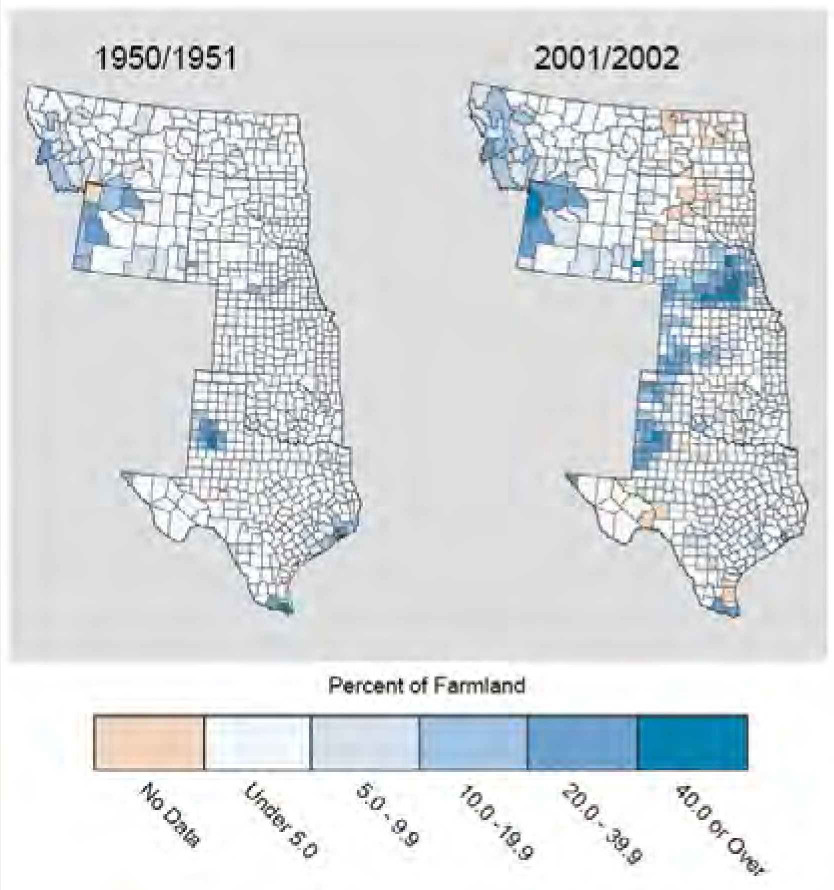

Figure 19.6. Irrigation in western Kansas, Oklahoma, and Texas supports crop development in semiarid areas. Declining aquifer levels threaten the ability to maintain production. Some aquifer-dependent regions, like southeastern Nebraska, have seen steep rises in irrigated farmland, from around 5% to more than 40%, during the period shown. (Figure source: reproduced from Atlas of the Great Plains by Stephen J. Lavin, Clark J. Archer, and Fred M. Shelley by permission of the University of Nebraska. Copyright 2011 by the Board of Regents of the University of Nebraska[33]).

The projected increase in high temperature extremes and heat waves will negatively affect livestock and concentrated animal feeding operations.[31] Shortened dormancy periods for winter wheat will lessen an important source of feed for the livestock industry. Climate change may thus result in a northward shift of crop and livestock production in the region. In areas projected to be hotter and drier in the future, maintaining agriculture on marginal lands may become too costly.

Adding to climate change related stresses, growing water demands from large urban areas are also placing stresses on limited water supplies. Options considered in some areas include groundwater development and purchasing water rights from agricultural areas for transfer to cities.[32]

During the droughts of 2011 and 2012, ranchers liquidated large herds due to lack of food and water. Many cattle were sold to slaughterhouses; others were relocated to other pastures through sale or lease. As herds are being rebuilt, there is an opportunity to improve genetic stock, as those least adapted to the drought conditions were the first to be sold or relocated. Some ranchers also used the drought as an opportunity to diversify their portfolio, managing herds in both Texas and Montana.

Key Message 3: Conservation and Adaptation

Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.

Land development for energy production, land transformations on the fringes of urban areas, and economic pressures to remove lands from conservation easements pose threats to natural systems in the Great Plains.[34] Habitat fragmentation is already a serious issue that inhibits the ability of species to migrate as climate variability and change alter local habitats.[35] Lands that remain out of production are susceptible to invasion from non-native plant species.

Many plant and animal species are responding to rising temperatures by adjusting their ranges at increasingly greater rates.[36] These adjustments may also require movement of species that have evolved to live in very specific habitats, which may prove increasingly difficult for these species. The historic bison herds migrated to adapt to climate, disturbance, and associated habitat variability,[37] but modern land-use patterns, roads, agriculture, and structures inhibit similar large-scale migration.[38] In the playa regions of the southern Great Plains, agricultural practices have modified more than 70% of seasonal lakes larger than 10 acres, and these lakes will be further altered under warming conditions.[39,40] These changes in seasonal lakes will further affect bird populations[41] and fish populations[42] in the region.

Observed climate-induced changes have been linked to changing timing of flowering, increases in wildfire activity and pest outbreaks, shifts in species distributions, declines in the abundance of native species, and the spread of invasive species (Ch. 8: Ecosystems). From Texas to Montana, altered flowering patterns due to more frost-free days have increased the length of pollen season for ragweed by as many as 16 days over the period from 1995 to 2009.[43] Earlier snowmelt in Wyoming from 1961 to 2002 has been related to the American pipit songbird laying eggs about 5 days earlier.[44] During the past 70 years, observations indicate that winter wheat is flowering 6 to 10 days earlier as spring temperatures have risen.[23] Some species may be less sensitive to changes in temperature and precipitation, causing first flowering dates to change for some species but not for others.[22] Even small shifts in timing, however, can disrupt the integrated balance of ecosystem functions like predator-prey relationships, mating behavior, or food availability for migrating birds.

In addition to climate changes, the increase in atmospheric CO_2 concentrations may offset the drying effects from warming by considerable improvements in plant water-use efficiency, which occur as CO_2 concentrations increase.[45] However, nutrient content of the grassland communities may be decreased under enriched CO_2 environments, affecting nutritional quality of the grasses and leaves eaten by animals.

The interaction of climate and land-use changes across the Great Plains promises to be challenging and contentious. Opportunities for conservation of native grasslands, including species and processes, depend primarily and most immediately on managing a fragmented network of untilled prairie. Restoration of natural processes, conservation of remnant species and habitats, and consolidation/connection of fragmented areas will facilitate conservation of species and ecosystem services across the Great Plains. However, climate change will complicate current conservation efforts as land fragmentation continues to reduce habitat connectivity. The implementation of adaptive management approaches provides robust options for multiple solutions.

SAGE GROUSE AND CLIMATE CHANGE

Habitat fragmentation inhibits the ability of species such as the Greater Sage Grouse, a candidate for Endangered Species Act protections, to migrate in response to climate change. Its current habitat is threatened by energy development, agricultural practices, and urban development. Rapid expansion of oil and gas fields in North Dakota, Wyoming, and Montana and development of wind farms from North Dakota through Texas are opening new lands to development and contributing to habitat fragmentation of important core Sage Grouse habitat.[46] The health of Sage Grouse habitat is associated with other species' health as well.[47] Climate change projections also suggest a shift in preferred habitat locations and increased susceptibility to West Nile Virus.[48]

Historical and Current Range of Sage Grouse Habitat

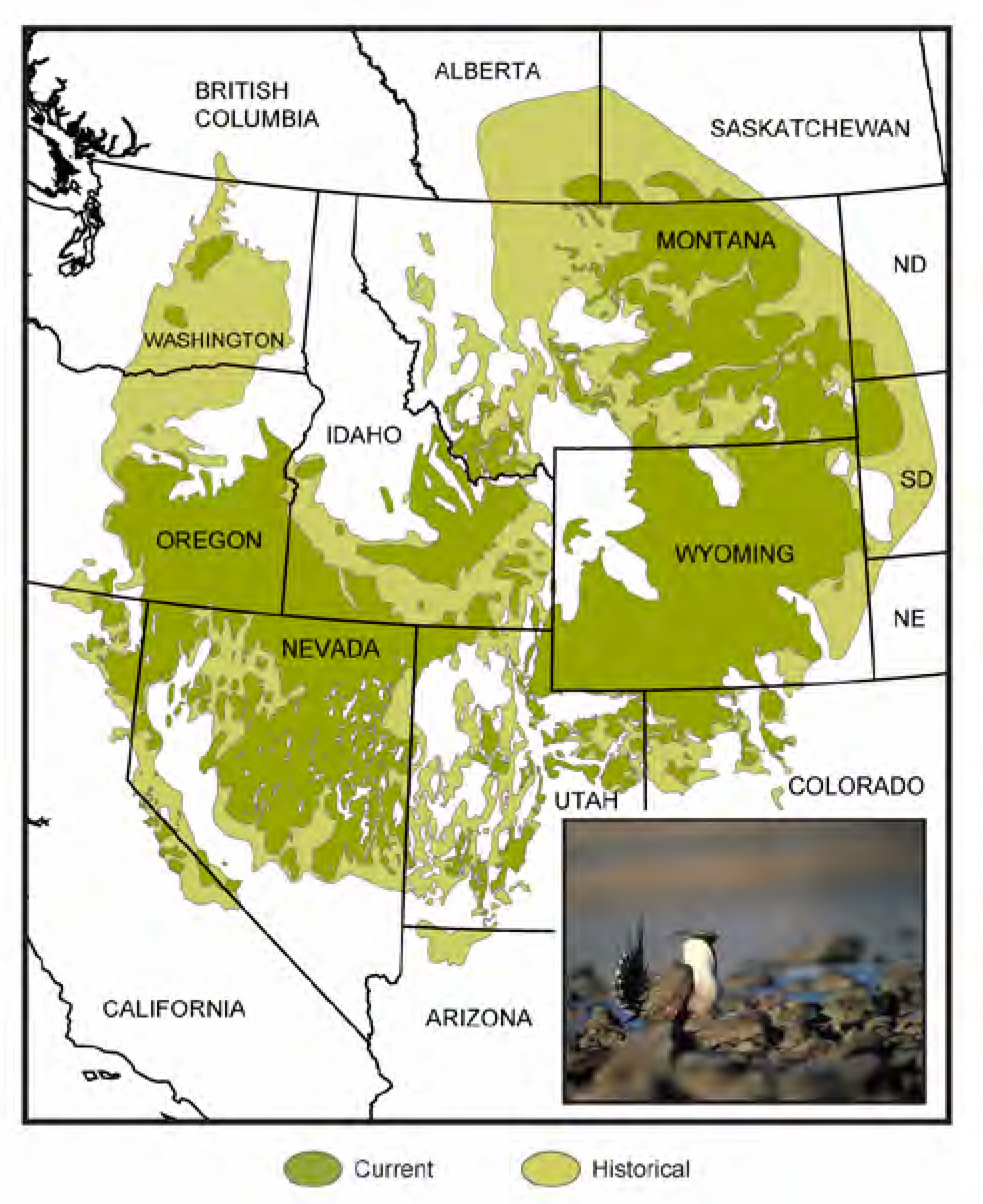

Figure 19.7. Comparing estimates of Greater Sage Grouse distribution from before settlement of the area (light green: prior to about 1800) with the current range (dark green: 2000) shows fragmentation of the sagebrush habitat required by this species. Over the last century, the sagebrush ecosystem has been altered by fire, invasion by new plant species, and conversion of land to agriculture, causing a decline in Sage Grouse populations. (Figure source: adapted from Aldridge et al. 2008.[49] Photo credit: U.S. Fish and Wildlife Service, Wyoming Ecological Services).

Key Message 4: Vulnerable Communities

Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.

The Great Plains is home to a geographically, economically, and culturally diverse population. For rural and tribal communities, their remote locations, sparse development, limited local services, and language barriers present greater challenges in responding to climate extremes. Working-age people are moving to urban areas, leaving a growing percentage of elderly people in rural communities (see also Ch. 14: Rural Communities).

Overall population throughout the region is stable or declining, with the exception of substantial increases in urban Texas, tribal communities, and western North Dakota, related in large part to rapid expansion of energy development.[50] Growing urban areas require more water, expand into forests and cropland, fragment habitat, and are at a greater risk of wildfire – all factors that interplay with climate.

Populations such as the elderly, low-income, and non-native English speakers face heightened climate vulnerability. Public health resources, basic infrastructure, adequate housing, and effective communication systems are often lacking in com-

Population Change in the Great Plains

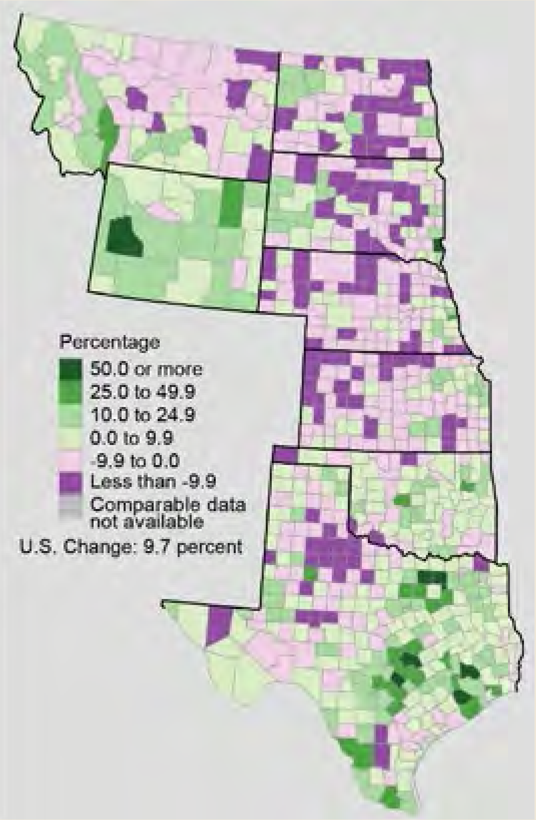

Figure 19.8. Demographic shifts continue to reshape communities in the Great Plains, with many central Great Plains communities losing residents. Rural and tribal communities will face additional challenges in dealing with climate change impacts due to demographic changes in the region (Ch. 14: Rural Communities; Ch. 12: Indigenous Peoples). Figure shows population change from 2000 to 2010. (Figure source: U.S. Census Bureau 2010[57]).

Tribal Populations in the Great Plains

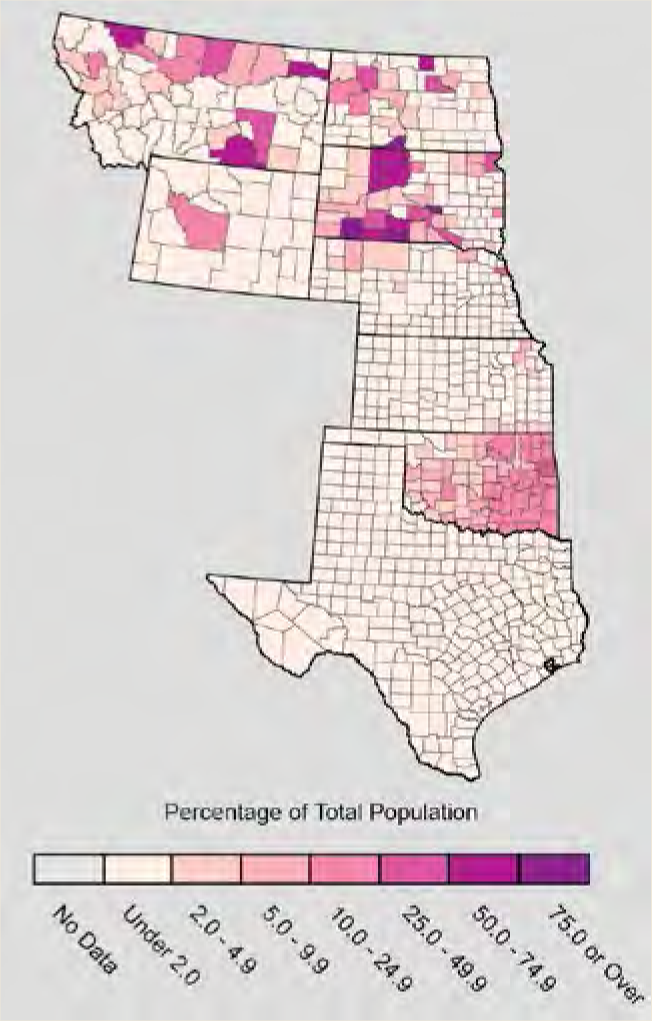

Figure 19.9. Tribal populations in the Great Plains are concentrated near large reservations, like various Sioux tribes in South Dakota and Blackfeet and Crow reservations in Montana; and in Cherokee, Chickasaw, Choctaw, and other tribal lands in Oklahoma (Figure source: reproduced from Atlas of the Great Plains by Stephen J. Lavin, Clark J. Archer, and Fred M. Shelley by permission of the University of Nebraska. Copyright 2011 by the Board of Regents of the University of Nebraska[33]).

munities that are geographically, politically, and economically isolated.[51] Elderly people are more vulnerable to extreme heat, especially in warmer cities and communities with minimal air conditioning or sub-standard housing.[52] Language barriers for Hispanics may impede their ability to plan for, adapt to, and respond to climate-related risks.[53]

The 70 federally recognized tribes in the Great Plains are diverse in their land use, with some located on lands reserved from their traditional homelands, and others residing within territories designated for their relocation, as in Oklahoma (see also Ch. 12: Indigenous Peoples). While tribal communities have adapted to climate change for centuries, they are now constrained by physical and political boundaries.[54] Traditional ecosystems and native resources no longer provide the support they used to.[55] Tribal members have reported the decline or disappearance of culturally important animal species, changes in the timing of cultural ceremonies due to earlier onset of spring, and the inability to locate certain types of ceremonial wild plants.[56]

Key Message 5: Opportunities to Build Resilience

The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.

The Great Plains is an integrated system. Changes in one part, whether driven by climate or by human decisions, affect other parts. Some of these changes are already underway, and many pieces of independent evidence project that ongoing climate-related changes will ripple throughout the region.

Many of these challenges will cut across sectors: water, land use, agriculture, energy, conservation, and livelihoods. Competition for water resources will increase within already-stressed human and ecological systems, particularly in the Southern Plains, affecting crops, energy production, and how well people, animals, and plants can thrive. The region's ecosystems, economies, and communities will be further strained by increasing intensity and frequency of floods, droughts, and heat waves that will penetrate into the lives and livelihoods of Great Plains residents. Although some communities and

OGLALA LAKOTA RESPOND TO CLIMATE CHANGE

The Oglala Lakota tribe in South Dakota is incorporating climate change adaptation and mitigation planning as they consider long-term sustainable development planning. Their *Oyate Omniciye* plan is a partnership built around six livability principles related to transportation, housing, economic competitiveness, existing communities, federal investments, and local values. Interwoven with this is a vision that incorporates plans to reduce future climate change and adapt to future climate change, while protecting cultural resources.[58]


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states have made efforts to plan for these projected changes, the magnitude of the adaptation and planning efforts do not match the magnitude of the expected changes.

Successful adaptation of human and natural systems to climate change would benefit from:

- recognition of and commitment to addressing these challenges;
- regional-scale planning and local-to-regional implementation;[8,59]
- mainstreaming climate planning into existing natural resource, public health, and emergency management processes;[60]
- renewed emphasis on restoration of ecological systems and processes;[61]
- recognition of the value of natural systems to sustaining life;[62,63]
- sharing information among decision-makers; and
- enhanced alignment of social and ecological goals.[64]

Communities already face tradeoffs in efforts to make efficient and sustainable use of their resources. Jobs, infrastructure, and tax dollars that come with fossil fuel extraction or renewable energy production are important, especially for rural communities. There is also economic value in the conversion of native grasslands to agriculture. Yet the tradeoffs among this development, the increased pressure on water resources, and the effects on conservation need to be considered if the region is to develop climate-resilient communities.

Untilled prairies used for livestock grazing provide excellent targets for native grassland conservation. Partnerships among many different tribal, federal, state, local, and private landowners can decrease landscape fragmentation and help manage the connection between agriculture and native habitats. Soil and wetland restoration enhances soil stability and health, water conservation, aquifer recharge, and food sources for wildlife and cattle. Healthy species and ecosystem services support social and economic systems where local products, tourism, and culturally significant species accompany large-scale agriculture, industry, and international trade as fundamental components of society.

Although there is tremendous adaptive potential among the diverse communities of the Great Plains, many local government officials do not yet recognize climate change as a problem that requires proactive planning.[60,65] Positive steps toward greater community resilience have been achieved through local and regional collaboration and increased two-way communication between scientists and local decision-makers (see Ch. 28: Adaptation). For example, the Institute for Sustainable Communities conducts Climate Leadership Academies that promote peer learning and provides direct technical assistance to communities in a five-state region in the Southwest as part of their support of the Western Adaptation Alliance.[66] Other regions have collaborated to share information, like the Southeast Florida Regional Compact 2012. Programs such as NOAA's Regional Integrated Sciences and Assessments (RISA) support scientists working directly with communities to help build capacity to prepare for and adapt to both climate variability and climate change.[67] Climate-related challenges can be addressed with creative local engagement and prudent use of community assets.[68] These assets include social networks, social capital, indigenous and local knowledge, and informal institutions.

The summer of 2011

Future climate change projections include more precipitation in the Northern Great Plains and less in the Southern Great Plains. In 2011, such a pattern was strongly manifest, with exceptional drought and recording-setting temperatures in Texas and Oklahoma and flooding in the Northern Great Plains.

Many locations in Texas and Oklahoma experienced more than 100 days over 100ºF. Both states set new records for the hottest summer since record keeping began in 1895. Rates of water loss due in part to evaporation were double the long-term average. The heat and drought depleted water resources and contributed to more than $10 billion in direct losses to agriculture alone. These severe water constraints strained the ability to meet electricity demands in Texas during 2011 and into 2012, a problem exacerbated by the fact that Texas is nearly isolated from the national electricity grid.

These recent temperature extremes were attributable in part to human-induced climate change (approximately 20% of the heat wave magnitude and a doubling of the chance that it would occur).[69] In the future, average temperatures in this region are expected to increase and will continue to contribute to the intensity of heat waves (Ch. 2: Our Changing Climate, Key Messages 3 and 7).

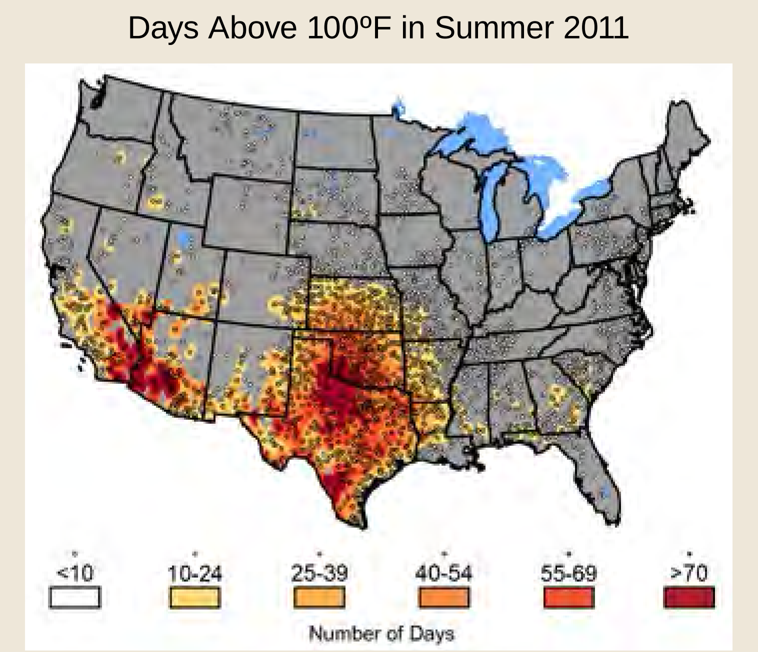

Figure 19.10. In 2011, cities including Houston, Dallas, Austin, Oklahoma City, and Wichita, among others, all set records for the highest number of days recording temperatures of 100ºF or higher in those cities' recorded history. The black circles denote the location of observing stations recording 100ºF days. (Figure source: NOAA NCDC 2012[3]).

By contrast to the drought in the Southern Plains, the Northern Plains were exceptionally wet in 2011, with Montana and Wyoming recording all-time wettest springs and the Dakotas and Nebraska not far behind. Record rainfall and snowmelt combined to push the Missouri River and its tributaries beyond their banks and leave much of the Crow Reservation in Montana underwater. The Souris River near Minot, North Dakota, crested at four feet above its previous record, with a flow five times greater than any in the past 30 years. Losses from the flooding were estimated at $2 billion.


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A Texas State Park police officer walks across a cracked lakebed in August 2011. This lake once spanned more than 5,400 acres.


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Increases in heavy downpours contribute to flooding.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

A central component of the assessment process was the Great Plains Regional Climate assessment workshop that was held in August 2011 in Denver, CO, with approximately 40 attendees. The workshop began the process leading to a foundational Technical Input Report (TIR), the Great Plains Regional Climate Assessment Technical Report.[5] The TIR consists of 18 chapters assembled by 37 authors representing a wide range of inputs including governmental agencies, non-governmental organizations, tribes, and other entities.

The chapter author team engaged in multiple technical discussions via regular teleconferences. These included careful review of the foundational TIR[8] and of approximately 50 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions were followed by expert deliberation of draft key messages by the authors during an in-person meeting in Kansas City in April 2012, wherein each message was defended before the entire author team prior to the key message being selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities".

KEY MESSAGE #1 TRACEABLE ACCOUNT

Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Temperatures are rising across the United States (Ch. 2: Our Changing Climate, Key Message 3 and its Traceable Account). Specific details for the Great Plains are provided in the Regional Climate Trends and Scenarios for the U.S. National Climate Assessment[4] with its references.

Rising temperatures impact energy and water (Ch.10: Energy, Water, and Land; Ch. 4: Energy). Publications have explored the projected increase in water competition and stress for natural resources[7,13,14,17] and the fragmentation of natural habitats and agricultural lands.[8] These sources provided numerous references that were drawn from to lead to this key message.

New information and remaining uncertainties

A key uncertainty is the exact rate and magnitude of the projected changes in precipitation, because high inter-annual variability may either obscure or highlight the long-term trends over the next few years.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Also unknown is ecological demand for water. Water use by native and invasive species under current climate needs to be quantified so that it can be modeled under future scenarios to map out potential impact envelopes. There is also uncertainty over the projections of changes in precipitation due to difficulty of modeling projections of convective precipitation, which is the primary source of water for most of the Great Plains.

Assessment of confidence based on evidence

Very High for all aspects of the key message. The relationship between increased temperatures and higher evapotranspiration is well established. Model projections of higher temperatures are robust. Confidence is highest for the southern Great Plains, where competition among sectors, cities, and states for future supply is already readily apparent, and where population growth (demand-side) and projected increases in precipitation deficits are greatest.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Great Plains Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for altered precipitation across the U.S. is discussed in Ch. 2: Our Changing Climate, Key Message 5 and 6 and their Traceable Accounts. Specific details for the Great Plains, such as warming winters and altered rainfall events are in the Climate Trends and Scenarios for the U.S. National Climate Assessment[4] with its references.

Limitations of irrigation options in the High Plains aquifer have been detailed.[21] The impacts of shifting from irrigated to rain-fed agriculture have also been detailed.[30] Studies document negative impacts on livestock production through the Great Plains.[31]

New information and remaining uncertainties

A key issue (uncertainty) is rainfall patterns. Although models show a general increase in the northern Great Plains and a decrease in the southern Great Plains, the diffuse gradient between the two leaves uncertain the location of greatest impacts on the hydrologic cycle. Timing of precipitation is critical to crop planting, development and harvesting; shifts in seasonality of precipitation therefore need to be quantified. Rainfall patterns will similarly affect forage production, particularly winter wheat that is essential to cattle production in the southern Great Plains.

Assessment of confidence based on evidence

The general pattern of precipitation changes and overall increases in temperature are robust. The implications of these changes are enormous, although assessing changes in more specific locations is more uncertain. Our assessment is based on the climate projections and known relationships to crops (for example, corn not being able to "rest" at night due to high minimum temperatures), but pinpointing where these impacts will occur is difficult. Additionally, other factors that influence productivity, such as genetics, technological change, economic incentives, and federal and state policies, can alter or accelerate the impacts. Given the evidence and remaining uncertainties, agriculture and livestock management practices will need to adjust to these changes in climate and derived aspects although specific changes are yet to be determined. Overall, confidence is **high**.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Great Plains Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of publications have explored the changes in habitat composition,[39] plant distribution and development cycles [22,23,43] and animal distributions.[36,38,44]

New information and remaining uncertainties

In general, the anticipated carbon dioxide enrichment, warming, and increase in precipitation variability influence vegetation primarily by affecting soil-water availability to plants. This is especially important as the transition between water surplus and water deficit (based on precipitation minus evapotranspiration) occurs across the Great Plains, with eastern areas supporting more biomass than western areas, especially given the current east-to-west difference in precipitation and the vegetation it supports.[1] These effects are evident in experiments with each of the individual aspects of climate change.[45] It is difficult to project, however, all of the interactions with all of the vegetative species of the Great Plains, so as to better manage ecosystems.

Several native species have been in decline due to habitat fragmentation, including quail, ocelots, and lesser prairie chickens.[46] Traditional adaptation methods of migration common to the Great Plains, such as bison herds had historically done, are less of an option as animals are confined to particular locations due to habitat fragmentation. As habitats change due to invasive species of plant and animals and as climate change reduces viability of native vegetation, the current landscapes may be incapable of supporting these wildlife populations.[38]

Assessment of confidence based on evidence

Confidence is **very high** that landscape is already fragmented and will continue to become more fragmented as energy exploration expands into less suitable agriculture lands that have not been developed as extensively. The effects of carbon dioxide and water availability on individual species are well known, but there is less published research on the interaction among different species. Evidence for the impact of climate change on species is **very high**, but specific adaptation strategies used by these species are less certain. Because of the more limited knowledge on adaptation strategies, we rate this key message overall has having **high** confidence. Our assessment is based upon historical methods, such as migration, used by species across the Great Plains to adapt to previous changes in climate and habitats and the incompatibility of those methods with current land-use practices.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Extreme events are documented for the nation (Ch. 2: Our Changing Climate, Key Message 7), and for the region in the Climate Trends and Scenarios for the U.S. National Climate Assessment.[4]

There are a few studies documenting the vulnerability of communities in remote locations with sparse infrastructure, limited local services, and aging populations (Ch. 14: Rural Communities),[51] with some areas inhibited by language barriers.[53] Changes in the tribal communities have been documented on a number of issues.[54,55,56,58]

New information and remaining uncertainties

A key issue (uncertainty) is how limited financial resources will be dedicated to adaptation actions and the amount of will and attention that will be paid to decreasing vulnerability and increasing resilience throughout the region. Should the awareness of damage grow great enough, it may overcome the economic incentives for development and change perspectives, allowing for increased adaptive response. But if current trends continue, more vulnerable lands may be lost. Thus the outcome on rural and vulnerable populations is largely unknown.

Assessment of confidence based on evidence

Extensive literature exists on vulnerable populations, limited resources and ability to respond to change. However, because the expected magnitude of changes is beyond previous experience and societal response is unknown, so the overall confidence is **high**.

KEY MESSAGE #5 TRACEABLE ACCOUNT

The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Great Plains Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

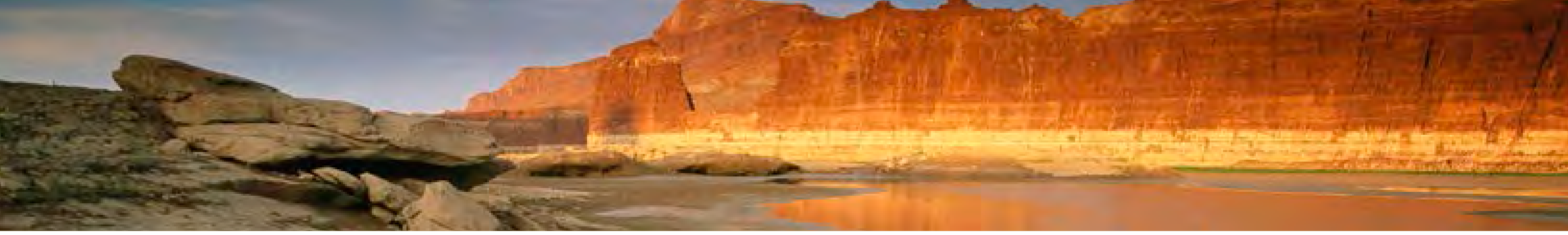
A number of publications have looked at the requirements for adaptation of human and natural systems to climate change. These requirements include large- and small-scale planning,[8,59,62] emphasis on restoring ecological systems and processes,[61] realizing the importance of natural systems,[62,63] and aligning the social and ecological goals.[64]

New information and remaining uncertainties

No clear catalog of ongoing adaptation activities exists for the Great Plains region. Initial steps towards such a catalog have been supported by the National Climate Assessment in association with NOAA's Regional Integrated Sciences and Assessments teams. The short-term nature of many planning activities has been described.[65] Until a systematic assessment is conducted, most examples of adaptation are anecdotal. However, stresses in physical and social systems are readily apparent, as described in the other key messages. How communities, economic sectors, and social groups will respond to these stresses needs further study.

Assessment of confidence based on evidence

Climate trends over the past century, such as North Dakota warming more than any other state in the contiguous U.S., coupled with evidence of ecological changes and projections for further warming indicates **very high** confidence that climate patterns will be substantially different than those of the preceding century. While systematic evidence is currently lacking, emerging studies point toward a proclivity toward short-term planning and incremental adjustment rather than long-term strategies for evolving agricultural production systems, habitat management, water resources and societal changes. Evidence suggests that adaptation is *ad hoc* and isolated and will likely be inadequate to address the magnitude of social, economic, and environmental challenges that face the region. Overall confidence is **medium**.



Climate Change Impacts in the United States

CHAPTER 20
SOUTHWEST

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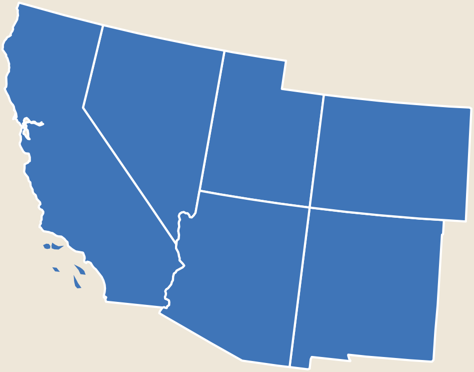

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On the Web: http://nca2014.globalchange.gov/report/regions/southwest

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

20 SOUTHWEST

Key Messages

1. **Snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems.**
2. **The Southwest produces more than half of the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increasing temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.**
3. **Increased warming, drought, and insect outbreaks, all caused by or linked to climate change, have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.**
4. **Flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some California coastal areas during storms and extreme high tides. Sea level rise is projected to increase as Earth continues to warm, resulting in major damage as wind-driven waves ride upon higher seas and reach farther inland.**
5. **Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in southwestern cities, which are home to more than 90% of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.**

The Southwest is the hottest and driest region in the United States, where the availability of water has defined its landscapes, history of human settlement, and modern economy. Climate changes pose challenges for an already parched region that is expected to get hotter and, in its southern half, significantly drier. Increased heat and changes to rain and snowpack will send ripple effects throughout the region's critical agriculture sector, affecting the lives and economies of 56 million people – a population that is expected to increase 68% by 2050, to 94 million.[1] Severe and sustained drought will stress water sources, already over-utilized in many areas, forcing increasing competition among farmers, energy producers, urban dwellers, and plant and animal life for the region's most precious resource.

The region's populous coastal cities face rising sea levels, extreme high tides, and storm surges, which pose particular risks to highways, bridges, power plants, and sewage treatment plants. Climate-related challenges also increase risks to critical port cities, which handle half of the nation's incoming shipping containers.

Agriculture, a mainstay of the regional and national economies, faces uncertainty and change. The Southwest produces more than half of the nation's high-value specialty crops, including certain vegetables, fruits, and nuts. The severity of future impacts will depend upon the complex interaction of pests, water supply, reduced chilling periods, and more rapid changes in the seasonal timing of crop development due to projected warming and extreme events.

Climate changes will increase stress on the region's rich diversity of plant and animal species. Widespread tree death


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and fires, which already have caused billions of dollars in economic losses, are projected to increase, forcing wholesale changes to forest types, landscapes, and the communities that depend on them (see also Ch. 7: Forests).

Tourism and recreation, generated by the Southwest's winding canyons, snow-capped peaks, and Pacific Ocean beaches, provide a significant economic force that also faces climate change challenges. The recreational economy will be increasingly affected by reduced streamflow and a shorter snow season, influencing everything from the ski industry to lake and river recreation.

Observed and Projected Climate Change

The Southwest is already experiencing the impacts of climate change. The region has heated up markedly in recent decades, and the period since 1950 has been hotter than any comparably long period in at least 600 years (Ch. 2: Our Changing Climate, Key Message 3).[2,3,4] The decade 2001-2010 was the warmest in the 110-year instrumental record, with temperatures almost 2°F higher than historic averages, with fewer cold air outbreaks and more heat waves.[4] Compared to relatively uniform regional temperature increases, precipitation trends vary considerably across the region, with portions experiencing decreases and others experiencing increases (Ch. 2: Our Changing Climate, Key Message 5).[4] There is mounting evidence that the combination of human-caused temperature increases and recent drought has influenced widespread tree mortality,[6,7] increased fire occurrence and area burned,[8] and forest insect outbreaks (Ch. 7: Forests).[9] Human-caused temperature increases and drought have also caused earlier spring snowmelt and shifted runoff to earlier in the year.[10]

Regional annual average temperatures are projected to rise by 2.5°F to 5.5°F by 2041-2070 and by 5.5°F to 9.5°F by 2070-2099 with continued growth in global emissions (A2 emissions scenario), with the greatest increases in the summer and fall (Figure 20.1). If global emissions are substantially reduced (as in the B1 emissions scenario), projected temperature increases are 2.5°F to 4.5°F (2041-2070), and 3.5°F to 5.5°F (2070-2099). Summertime heat waves are projected to become longer and hotter, whereas the trend of decreasing wintertime cold air outbreaks is projected to continue (Ch. 2: Our Changing Climate, Key Message 7).[11,12] These changes will directly affect urban public health through increased risk of heat stress, and urban infrastructure through increased risk of disruptions to electric power generation.[13,14,15,16] Rising temperatures also have direct impacts on crop yields and productivity of key regional crops, such as fruit trees.

Projected Temperature Increases

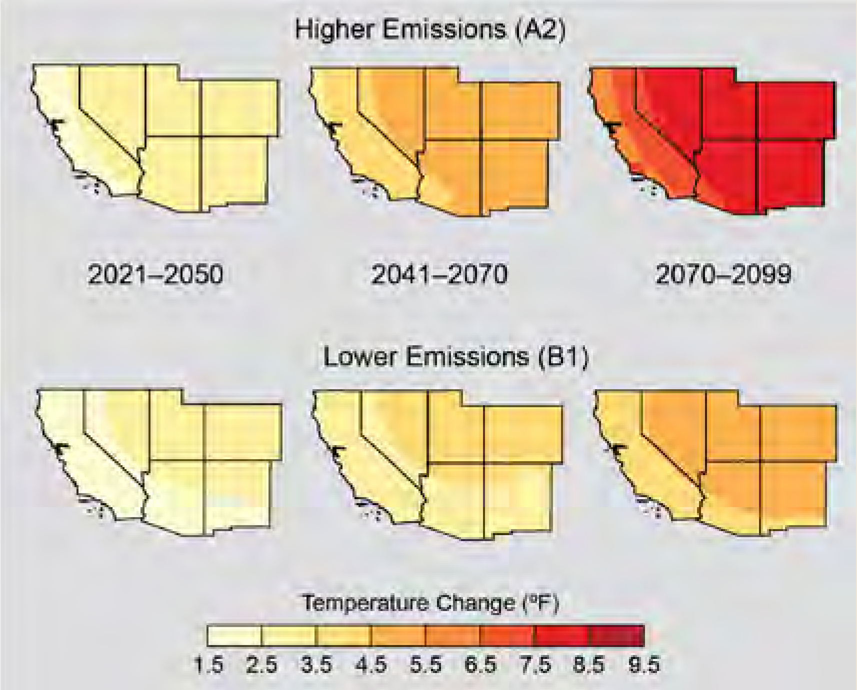

Figure 20.1. Maps show projected changes in average, as compared to 1971-1999. Top row shows projections assuming heat-trapping gas emissions continue to rise (A2). Bottom row shows projections assuming substantial reductions in emissions (B1). (Figure source: adapted from Kunkel et al. 2013[17]).

Projections of precipitation changes are less certain than those for temperature.[17,18] Under a continuation of current rising emissions trends (A2), reduced winter and spring precipitation is consistently projected for the southern part of the Southwest by 2100 as part of the general global precipitation reduction in subtropical areas. In the northern part of the region, projected winter and spring precipitation changes are smaller than natural variations. Summer and fall changes are also smaller than natural variations throughout the region (Ch. 2: Our Changing Climate, Key Message 5).[17] An increase in winter flood hazard risk in rivers is projected due to increases in flows of atmospheric moisture into California's coastal ranges and the Sierra Nevada (Ch. 3: Water).[19] These "atmospheric rivers" have contributed to the largest floods in California history[20] and can penetrate inland as far as Utah and New Mexico.

The Southwest is prone to drought. Southwest paleoclimate records show severe mega-droughts at least 50 years long.[21] Future droughts are projected to be substantially hotter, and for major river basins such as the Colorado River Basin, drought is projected to become more frequent, intense, and longer lasting than in the historical record.[18] These drought conditions present a huge challenge for regional management of water resources and natural hazards such as wildfire. In light of climate change and water resources treaties with Mexico, discussions will need to continue into the future to address demand pressures and vulnerabilities of groundwater and surface water systems that are shared along the border.

VULNERABILITIES OF NATIVE NATIONS AND BORDER CITIES

The Southwest's 182 federally recognized tribes and communities in its U.S.-Mexico border region share particularly high vulnerabilities to climate changes such as high temperatures, drought, and severe storms. Tribes may face loss of traditional foods, medicines, and water supplies due to declining snowpack, increasing temperatures, and increasing drought (see also Ch 12: Indigenous Peoples).[22] Historic land settlements and high rates of poverty – more than double that of the general U.S. population[23] – constrain tribes' abilities to respond effectively to climate challenges.

Most of the Southwest border population is concentrated in eight pairs of fast-growing, adjacent cities on either side of the U.S.-Mexico border (like El Paso and Juárez) with shared problems. If the 24 U.S. counties along the entire border were aggregated as a 51st state, they would rank near the bottom in per capita income, employment rate, insurance coverage for children and adults, and high school completion.[24] Lack of financial resources and low tax bases for generating resources have resulted in a lack of roads and safe drinking water infrastructure, which makes it more daunting for tribes and border populations to address climate change issues. These economic pressures increase vulnerabilities to climate-related health and safety risks, such as air pollution, inadequate erosion and flood control, and insufficient safe drinking water.[25]

Key Message 1: Reduced Snowpack and Streamflows

Snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems.

Winter snowpack, which slowly melts and releases water in spring and summer, when both natural ecosystems and people have the greatest needs for water, is key to the Southwest's hydrology and water supplies. Over the past 50 years across most of the Southwest, there has been less late-winter precipitation falling as snow, earlier snowmelt, and earlier arrival of most of the year's streamflow.[26,27] Streamflow totals in the Sacramento-San Joaquin, the Colorado, the Rio Grande, and in the Great Basin were 5% to 37% lower between 2001 and 2010 than the 20th century average flows.[4] Projections of further reduction of late-winter and spring snowpack and subsequent reductions in runoff and soil moisture[28,29] pose increased risks to the water supplies needed to maintain the Southwest's cities, agriculture, and ecosystems.

Temperature-driven reductions in snowpack are compounded by dust and soot accumulation on the surface of snowpack. This layer of dust and soot, transported by winds from lowland regions, increases the amount of the sun's energy absorbed by the snow. This leads to earlier snowmelt and evaporation – both of which have negative implications for water supply, alpine vegetation, and forests.[30,31] The prospect of more lowland soil drying out from drought and human disturbances (like agriculture and development) makes regional dust a potent future risk to snow and water supplies.

In California, drinking water infrastructure needs are estimated at $4.6 billion annually over the next 10 years, even without considering the effects of climate change.[32] Climate change will increase the cost of maintaining and improving drinking

Projected Snow Water Equivalent

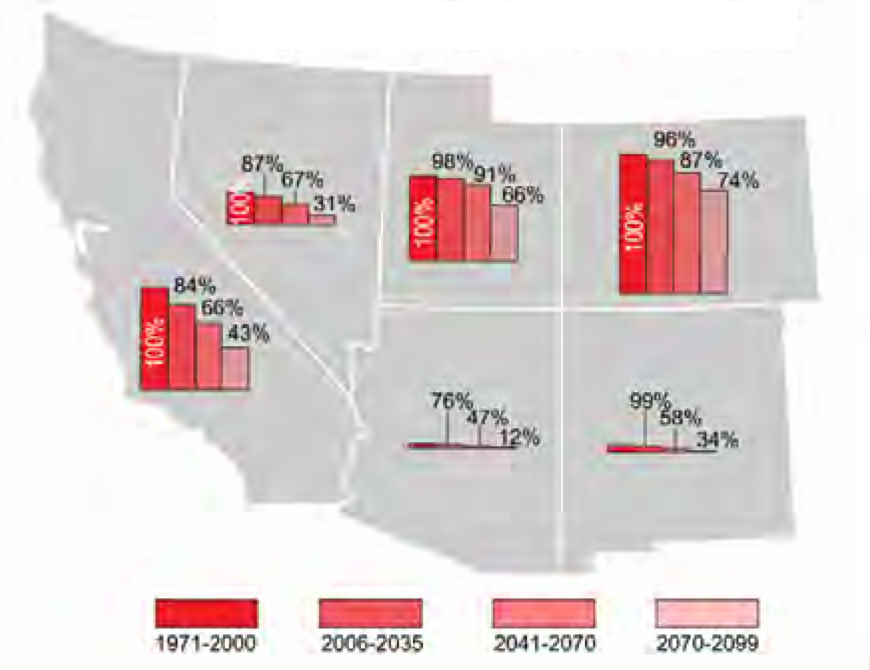

Figure 20.2. Snow water equivalent (SWE) refers to the amount of water held in a volume of snow, which depends on the density of the snow and other factors. Figure shows projected snow water equivalent for the Southwest, as a percentage of 1971-2000, assuming continued increases in global emissions (A2 scenario). The size of bars is in proportion to the amount of snow each state contributes to the regional total; thus, the bars for Arizona are much smaller than those for Colorado, which contributes the most to region-wide snowpack. Declines in peak SWE are strongly correlated with early timing of runoff and decreases in total runoff. For watersheds that depend on snowpack to provide the majority of the annual runoff, such as in the Sierra Nevada and in the Upper Colorado and Upper Rio Grande River Basins, lower SWE generally translates to reduced reservoir water storage. (Data from Scripps Institution of Oceanography).

water infrastructure, because expanded wastewater treatment and desalinating water for drinking are among the key strategies for supplementing water supplies.

Conservation efforts have proven to reduce water use, but are not projected to be sufficient if current trends for water supply and demand continue.[41] Large water utilities are currently attempting to understand how water supply and demand may change in conjunction with climate changes, and which adaptation options are most viable.[42,43]


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THE SOUTHWEST’S RENEWABLE POTENTIAL TO PRODUCE ENERGY WITH LESS WATER

The Southwest’s abundant geothermal, wind, and solar power-generation resources could help transform the region’s electric generating system into one that uses substantially more renewable energy. This transformation has already started, driven in part by renewable energy portfolio standards adopted by five of six Southwest states, and renewable energy goals in Utah. California’s law limits imports of baseload electricity generation from coal and oil and mandates reduction of heat-trapping greenhouse gas emissions to 1990 levels by 2020.[33]

As the regional climate becomes hotter and, in parts of the Southwest, drier, there will be less water available for the cooling of thermal power plants (Ch. 2: Our Changing Climate),[34] which use about 40% of the surface water withdrawn in the United States.[35] The projected warming of water in rivers and lakes will reduce the capacity of thermal power plants, especially during summer when electricity demand skyrockets.[36] Wind and solar photovoltaic installations could substantially reduce water withdrawals. A large increase in the portion of power generated by renewable energy sources may be feasible at reasonable costs,[37,38] and could substantially reduce water withdrawals (Ch. 10: Energy, Water, and Land).[39]

Scenario for Greenhouse Gas Emissions Reductions in the Electricity Sector

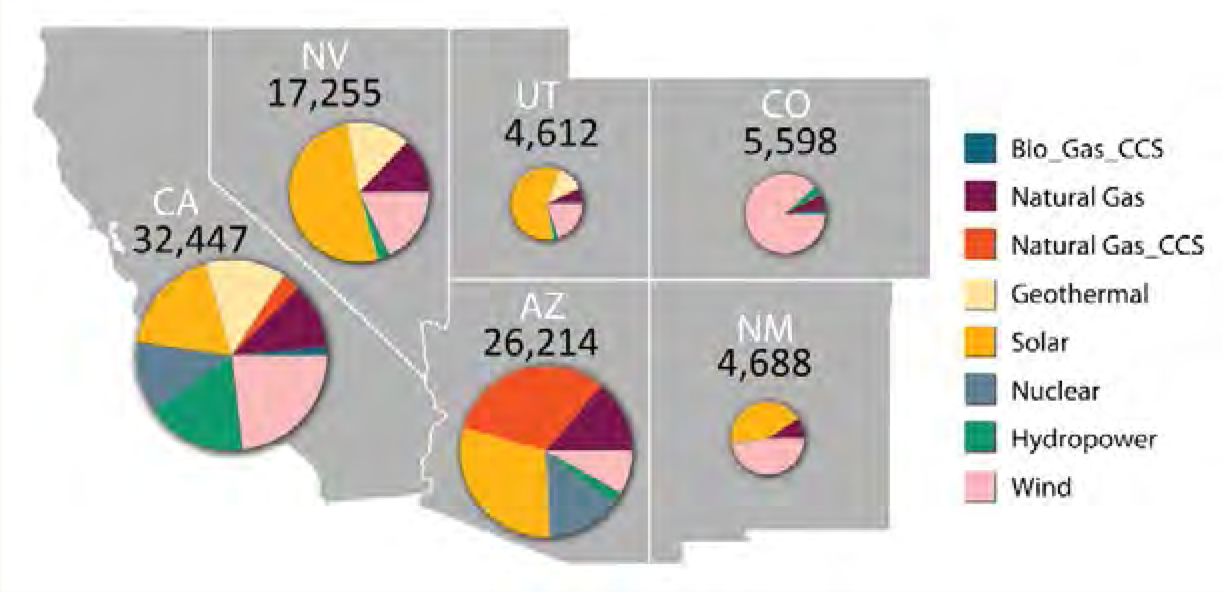

Figure 20.3. Major shifts in how electricity is produced can lead to large reductions in heat-trapping gas emissions. Shown is an illustrative scenario in which different energy combinations could, by 2050, achieve an 80% reduction of heat-trapping gas emissions from 1990 levels in the electricity sector in the Southwest. For each state, that mix varies, with the circle representing the average hourly generation in megawatts (the number above each circle) from 10 potential energy sources. CCS refers to carbon capture and storage. (Data from Wei et al. 2012, 2013[38,40]).

Key Message 2: Threats to Agriculture

The Southwest produces more than half of the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increasing temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.

Farmers are renowned for adapting to yearly changes in the weather, but climate change in the Southwest could happen faster and more extensively than farmers' ability to adapt. The region's pastures are rain-fed (non-irrigated) and highly susceptible to projected drought. Excluding Colorado, more than 92% of the region's cropland is irrigated, and agricultural uses account for 79% of all water withdrawals in the region.[44,45,46] A warmer, drier climate is projected to accelerate current trends of large transfers of irrigation water to urban areas,[47,48,49] which would affect local agriculturally dependent economies.

California produces about 95% of U.S. apricots, almonds, artichokes, figs, kiwis, raisins, olives, cling peaches, dried plums, persimmons, pistachios, olives, and walnuts, in addition to other high-value crops.[50] Drought and extreme weather affect the market value of fruits and vegetables more than other crops because they have high water content and because sales depend on good visual appearance.[51] The combination of a longer frost-free season, less frequent cold air outbreaks, and more frequent heat waves accelerates crop ripening and maturity, reduces yields of corn, tree fruit, and wine grapes, stresses livestock, and increases agricultural water consumption.[52,53] This combination of climate changes is projected to continue and intensify, possibly requiring a northward shift in crop production, displacing existing growers and affecting farming communities.[54,55]

Winter chill periods are projected to fall below the duration necessary for many California trees to bear nuts and fruits, which will result in lower yields.[56] Warm-season vegetable crops grown in Yolo County, one of California's biggest producers, may not be viable under hotter climate conditions.[54,57] Once temperatures increase beyond optimum growing thresholds, further increases in temperature, like those projected for the decades beyond 2050, can cause large decreases in crop yields and hurt the region's agricultural economy.

Longer Frost-Free Season Increases Stress on Crops

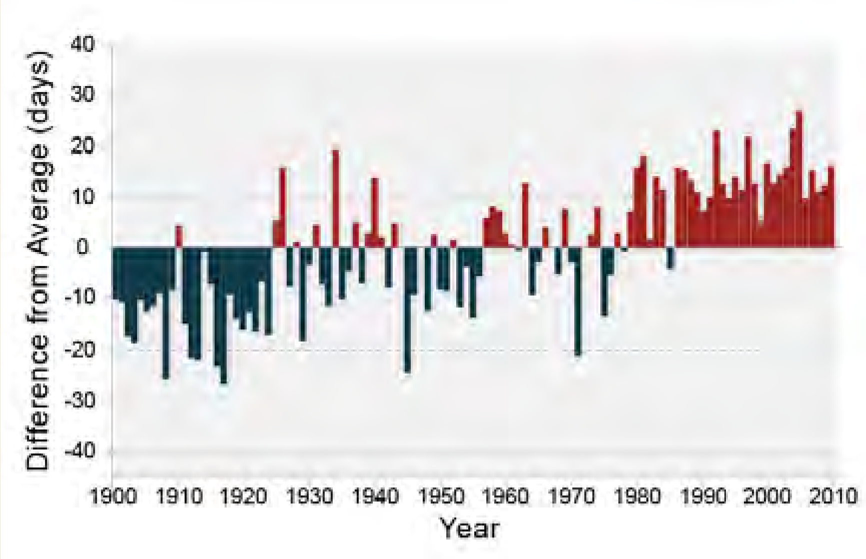

Figure 20.4. The frost-free season is defined as the period between the last occurrence of 32°F in spring and the first occurrence of 32°F in the subsequent fall. The chart shows significant increases in the number of consecutive frost-free days per year in the past three decades compared to the 1901-2010 average. Increased frost-free season length, especially in already hot and moisture-stressed regions like the Southwest, is projected to lead to further heat stress on plants and increased water demands for crops. Higher temperatures and more frost-free days during winter can lead to early bud burst or bloom of some perennial plants, resulting in frost damage when cold conditions occur in late spring (see Ch. 6: Agriculture); in addition, with higher winter temperatures, some agricultural pests can persist year-round, and new pests and diseases may become established.[47] (Figure source: Hoerling et al. 2013[4]).

Key Message 3: Increased Wildfire

Increased warming, drought, and insect outbreaks, all caused by or linked to climate change, have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.

Fire naturally shapes southwestern landscapes. Indeed, many Southwest ecosystems depend on periodic wildfire to maintain healthy tree densities, enable seeds to germinate, and reduce pests.[58] Excessive wildfire destroys homes, exposes slopes to erosion and landslides, threatens public health, and causes economic damage.[59,60] The $1.2 billion in damages from the 2003 Grand Prix fire in southern California illustrates the high cost of wildfires.[60]

Beginning in the 1910s, the Federal Government developed a national policy of attempting to extinguish every fire, which allowed wood and other fuels to over-accumulate[61] and urban development to encroach on fire-prone areas. These changes have also contributed to increasing fire risk.


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Increased warming due to climate change,[3] drought, insect infestations,[62] and accumulation of woody fuels and non-native grasses[63,64] make the Southwest vulnerable to increased wildfire. Climate outweighed other factors in determining burned area in the western U.S. from 1916 to 2003,[65] a finding confirmed by 3000-year long reconstructions of southwestern fire history.[66,67,68] Between 1970 and 2003, warmer and drier conditions increased burned area in western U.S. mid-elevation conifer forests by 650% (Ch. 7: Forests, Key Message 1).[8]

Drought and increased temperatures due to climate change have caused extensive tree death across the Southwest.[7,69] In addition, winter warming due to climate change has exacerbated bark beetle outbreaks by allowing more beetles, which normally die in cold weather, to survive and reproduce.[70] Wildfire and bark beetles killed trees across 20% of Arizona and New Mexico forests from 1984 to 2008.[62]

Numerous fire models project more wildfire as climate change continues.[64,71,72,73,74] Models project a doubling of burned area in the southern Rockies,[73] and up to a 74% increase in burned area in California,[74] with northern California potentially experiencing a doubling under a high emissions scenario toward the end of the century. Fire contributes to upslope shifting of vegetation, spread of invasive plants after extensive and intense fire, and conversion of forests to woodland or grassland.[63,75]

Historical and projected climate change makes two-fifths (40%) of the region vulnerable to these shifts of major vegetation types or biomes; notably threatened are the conifer forests of southern California and sky islands of Arizona.[71]

Prescribed burning, mechanical thinning, and retention of large trees can help some southwestern forest ecosystems adapt to climate change.[68,76] These adaptation measures also reduce emissions of the gases that cause climate change because long-term storage of carbon in large trees can outweigh short-term emissions from prescribed burning.[61,77]

Key Message 4: Sea Level Rise and Coastal Damage

Flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some California coastal areas during storms and extreme high tides. Sea level rise is projected to increase as Earth continues to warm, resulting in major damage as wind-driven waves ride upon higher seas and reach farther inland.

In the last 100 years, sea level has risen along the California coast by 6.7 to 7.9 inches.[78] In the last decade, high tides on top of this sea level rise have contributed to new damage to infrastructure, such as the inundation of Highway 101 near San Francisco and backup of seawater into the San Francisco Bay Area sewage systems.

Although sea level along the California coast has been relatively constant since 1980, both global and relative Southwest sea levels are expected to increase at accelerated rates.[78,79,80] During the next 30 years, the greatest impacts will be seen during high tides and storm events. Rising sea level will allow more wave energy to reach farther inland and extend high tide periods, worsening coastal erosion on bluffs and beaches and increasing flooding potential.[18,81,82,83,84]

The result will be impacts to the nation's largest ocean-based economy, which is estimated at $46 billion annually.[85,86] If adaptive action is not taken, coastal highways, bridges, and other transportation infrastructure (such as the San Francisco and Oakland airports) are at increased risk of flooding with a 16-inch rise in sea level in the next 50 years,[5] an amount consistent with the 1 to 4 feet of expected global increase in sea level (see Ch. 2: Our Changing Climate, Key Message 10). In Los Angeles, sea level rise poses a threat to groundwater supplies and estuaries,[82,87] by potentially contaminating groundwater with seawater, or increasing the costs to protect coastal freshwater aquifers.[88]

Projected increases in extreme coastal flooding as a result of sea level rise will increase human vulnerability to coastal flooding events. Currently, 260,000 people in California are at risk from what is considered a once-in-100-year flood.[82] With a sea level rise of about three feet (in the range of projections for this century – Ch. 2: Our Changing Climate, Key Message 10)[78,80] and at current population densities, 420,000 people would be at risk from the same kind of 100-year flood event,[85] based on existing exposure levels. Highly vulnerable populations

Coastal Risks Posed by Sea Level Rise and High Tides

Figure 20.5. King tides, which typically happen twice a year as a result of a gravitational alignment of the sun, moon, and Earth, provide a preview of the risks rising sea levels may present along California coasts in the future. While king tides are the extreme high tides today, with projected future sea level rise, this level of water and flooding will occur during regular monthly high tides. During storms and future king tides, more coastal flooding and damage will occur. The King Tide Photo Initiative encourages the public to visually document the impact of rising waters on the California coast, as exemplified during current king tide events. Photos show water levels along the Embarcadero in San Francisco, California during relatively normal tides (top), and during an extreme high tide or "king tide" (bottom). (Photo credit: Mark Johnsson).

– people less able to prepare, respond, or recover from natural disaster due to age, race, or income – make up approximately 18% of the at-risk population (Ch. 25: Coasts).[85,89]

The California state government, through its Ocean and Coastal Resources Adaptation Strategy, along with local governments, is using new sea level mapping and information about social vulnerability to undertake coastal adaptation planning. NOAA has created an interactive map showing areas that would be affected by sea level rise (http://www.csc.noaa.gov/slr/viewer/#).

Key Message 5: Heat Threats to Health

Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in southwestern cities, which are home to more than 90% of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.

The Southwest has the highest percentage of its population living in cities of any U.S. region. Its urban population rate, 92.7%, is 12% greater than the national average.[90] Increasing metropolitan populations already pose challenges to providing adequate domestic water supplies, and the combination of increased population growth and projected increased risks to surface water supplies will add further challenges.[91,92] Tradeoffs are inevitable between conserving water to help meet the demands of an increasing population and providing adequate water for urban greenery to reduce increasing urban temperatures.

Urban infrastructures are especially vulnerable because of their interdependencies; strains in one system can cause disruptions in another (Ch. 11: Urban, Key Message 2; Ch. 9: Human Health).[16,93] For example, an 11-minute power system disturbance in September 2011 cascaded into outages that left 1.5 million San Diego residents without power for 12 hours;[94] the outage disrupted pumps and water service, causing 1.9 million gallons of sewage to spill near beaches.[95] Extensive use of air conditioning to deal with high temperatures can quickly increase electricity demand and trigger cascading energy system failures, resulting in blackouts or brownouts.[14,15]

Urban Heat and Public Health

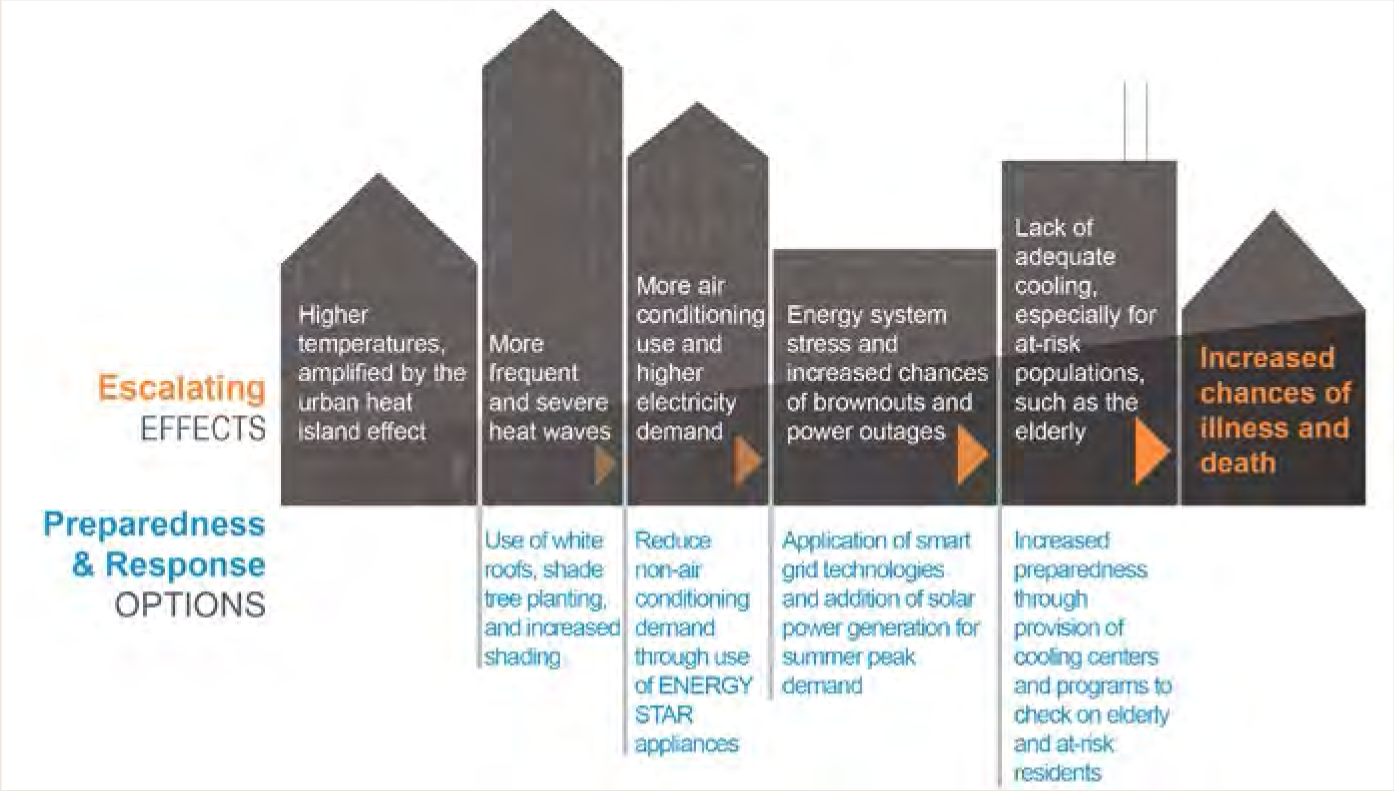

Figure 20.6. The projected increase in heat waves in Southwest cities (Ch. 2: Our Changing Climate, Key Message 7) increases the chances that a chain of escalating effects could lead to serious increases in illness and death due to heat stress. The top of the figure provides some of the links in that chain, while the bottom of the figure provides adaptation and improved governance options that can reduce this vulnerability and improve the resilience of urban infrastructure and community residents.

Heat stress, a recurrent health problem for urban residents, has been the leading weather-related cause of death in the United States since 1986, when record keeping began[96] – and the highest rates nationally are found in Arizona.[97] The effects of heat stress are greatest during heat waves lasting several days or more, and heat waves are projected to increase in frequency, duration, and intensity,[11,13,98] become more humid,[11] and cause a greater number of deaths.[99] Already, severe heat waves, such as the 2006 ten-day California event, have resulted in high mortality, especially among elderly populations.[100] In addition, evidence indicates a greater likelihood of impacts in less affluent neighborhoods, which typically lack shade trees and other greenery and have reduced access to air conditioning.[101]

Exposure to excessive heat can also aggravate existing human health conditions, like for those who suffer from respiratory or heart disease.[99] Increased temperatures can reduce air quality, because atmospheric chemical reactions proceed faster in warmer conditions. The outcome is that heat waves are often accompanied by increased ground-level ozone,[102] which can cause respiratory distress. Increased temperatures and longer warm seasons will also lead to shifts in the distribution of disease-transmitting mosquitoes (Ch. 9: Human Health, Key Message 1).[97]

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the assessment process was the Southwest Regional Climate assessment workshop that was held August 1-4, 2011, in Denver, CO with more than 80 participants in a series of scoping presentations and workshops. The workshop began the process leading to a foundational Technical Input Report (TIR) report.[103] The TIR consists of nearly 800 pages organized into 20 chapters that were assembled by 122 authors representing a wide range of inputs, including governmental agencies, non-governmental organizations, tribes, and other entities. The report findings were described in a town hall meeting at the American Geophysical Union's annual fall meeting in 2011, and feedback was collected and incorporated into the draft.

The chapter author team engaged in multiple technical discussions through more than 15 biweekly teleconferences that permitted a careful review of the foundational TIR[103] and of approximately 125 additional technical inputs provided by the public, as well as the other published literature and professional judgment. The chapter author team then met at the University of Southern California on March 27-28, 2012, for expert deliberation of draft key messages by the authors. Each key message was defended before the entire author team prior to the key message being selected for inclusion. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities, which include magnitude, timing, persistence and reversibility, likelihood and confidence, potential for adaptation, distribution, and importance of the vulnerable system."[104]

KEY MESSAGE #1 TRACEABLE ACCOUNT

Snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems.

Description of evidence base

The key message was chosen based on input from the extensive evidence documented in the Southwest Technical Input Report[103] and additional technical input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Key Message 5 in Chapter 2, Our Changing Climate, also provides evidence for declining precipitation across the United States, and a regional study[17] discusses regional trends and scenarios for the Southwest.

Over the past 50 years, there has been a reduction in the amount of snow measured on April 1 as a proportion of the precipitation falling in the corresponding water-year (October to September), which affects the timing of snowfed rivers. The implication of this finding is that the lower the proportion of April 1 snow water equivalent in the water-year-to-date precipitation, the more rapid the runoff, and the earlier the timing of center-of-mass of streamflow in snowfed rivers.[26,27] For the "recent decade" (2001 to 2010), snowpack evidence is from U.S. Department of Agriculture (USDA) Natural Resources Conservation Service snow course data, updated through 2010. One study[4] has analyzed streamflow amounts for the region's four major river basins, the Colorado, Sacramento-San Joaquin, Great Basin (Humboldt River, NV), and the Rio Grande; data are from the U.S. Department of the Interior – Bureau of Reclamation, California Department of Water Resources, U.S. Geological Survey, and the International Boundary and Water Commission (U.S. Section), respectively. These data are backed by a rigorous detection and attribution study.[10] Projected trends[18] make use of downscaled climate parameters for 16 global climate models (GCMs), and hydrologic projections for the Colorado River, Rio Grande, and Sacramento-San Joaquin River System.

Based on GCM projections, downscaled and run through the variable infiltration capacity (VIC) hydrological model,[105] there are projected reductions in spring snow accumulation and total annual runoff, leading to reduced surface water supply reliability for much of the Southwest, with greater impacts occurring during the second half of this century.[18,28]

Future flows in the four major Southwest rivers are projected to decline as a result of a combination of increased temperatures, increased evaporation, less snow, and less persistent snowpack. These changes have been projected to result in decreased surface water supplies, which will have impacts for allocation of water resources to major uses, such as urban drinking water, agriculture, and ecosystem flows.

New information and remaining uncertainties

Different model simulations predict different levels of snow loss. These differences arise because of uncertainty in climate change warming and precipitation projections due to differences among GCMs, uncertainty in regional downscaling, uncertainty in hydrological modeling, differences in emissions, aerosols, and other forcings, and because differences in the hemispheric and regional-scale atmospheric circulation patterns produced by different GCMs produce different levels of snow loss in different model simulations.

In addition to the aforementioned uncertainties in regional climate and hydrology projections, projection of future surface water supply reliability includes at least the following additional uncertainties: 1) changes in water management, which depend on agency resources and leadership and cooperation of review boards and the public;[106] 2) management responses to non-stationarity;[107] 3) legal, economic, and institutional options for augmenting existing water supplies, adding underground water storage and recovery infrastructure, and fostering further water conservation (for example, Udall 2013[108]); 4) adjudication of unresolved water rights; and 5) local, state, regional, and national policies related to the balance of agricultural, ecosystem, and urban water use (for example, Reclamation 2011[43]).

Assessment of confidence based on evidence

There is **high** confidence in the continued trend of declining snowpack and streamflow in parts of the Southwest given the evidence base and remaining uncertainties.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

For the impacts on water supply, there is **high** confidence that reduced surface water supply reliability will affect the region's cities, agriculture, and ecosystems.

Key Message #2 Traceable Account

The Southwest produces more than half of the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increasing temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.

Description of evidence base

Increased competition for scarce water was presented in the first key message and in the foundational Technical Input Report (TIR).[103] U.S. temperatures, including those for the Southwest region, have increased and are expected to continue to rise (Ch. 2: Our Changing Climate, Key Message 3). Heat waves have become more frequent and intense and droughts are expected to become more intense in the Southwest (Ch. 2: Our Changing Climate, Key Message 7). The length of the frost-free season in the Southwest has been increasing, and frost-free season length is projected to increase (Ch. 2: Our Changing Climate, Key Message 4). A regional study[17] discusses the trends and scenarios in the Southwest for moisture, cold, heat, and their extremes.

There is abundant evidence of irrigation dependence and vulnerability of high-value specialty crops to extremes of moisture, cold, and heat, including, prominently, the 2009 National Climate Assessment[109] and the foundational TIR.[103] Southwest agricultural production statistics and irrigation dependence of that production is delineated in the USDA 2007 Census of Agriculture[45] and the USDA Farm and Ranch Irrigation Survey.[46]

Reduced Yields. Even under the most conservative emissions scenarios evaluated (the combination of SRES B1emissions scenario with statistically downscaled winter chill projections from the HADCM3 climate model), one study[56] projected that required winter chill periods will fall below the number of hours that are necessary for many of the nut- and fruit-bearing trees of California, and yields are projected to decline as a result. A second study[54] found that California wheat acreage and walnut acreage will decline due to increased temperatures. Drought and extreme weather may have more effect on the market value of fruits and vegetables, as opposed to other crops, because fruits and vegetables have high water content and because consumers expect good visual appearance and flavor.[51] Extreme daytime and nighttime temperatures have been shown to accelerate crop ripening and maturity, reduce yield of crops such as corn, fruit trees, and vineyards, cause livestock to be stressed, and increase water consumption in agriculture.[53]

Irrigation water transfers to urban. Warmer, drier future scenarios portend large transfers of irrigation water to urban areas even though agriculture will need additional water to meet crop demands, affecting local agriculturally-dependent economies.[55] In particular areas of the Southwest (most notably lower-central Arizona), a significant reduction in irrigated agriculture is already underway as land conversion occurs near urban centers.[48] Functioning water markets, which may require legal and institutional changes, can enable such transfers and reduce the social and economic impacts of water shortages to urban areas.[47] The economic impacts of climate change on Southwest fruit and nut growers are projected to be substantial and will result in a northward shift in production of these crops, displacing growers and affecting communities.

New information and remaining uncertainties

Competition for water is an uncertainty. The extent to which water transfers take place depends on whether complementary investments in conveyance or storage infrastructure are made. Currently, there are legal and institutional restrictions limiting water transfers across state and local jurisdictions. It is uncertain whether infrastructure investments will be made or whether institutional innovations facilitating transfers will develop. Institutional barriers will be greater if negative third-party effects of transfers are not adequately addressed. Research that would improve the information base to inform future water transfer debates includes: 1) estimates of third party impacts, 2) assessment of institutional mechanisms to reduce those impacts, 3) environmental impacts of water infrastructure projects, and 4) options and costs of mitigating those environmental impacts.

Extremes and phenology. A key uncertainty is the timing of extreme events during the phenological stage of the plant or the growth cycle of the animal. For example, plants are more sensitive to extreme high temperatures and drought during the pollination stage compared to vegetative growth stages.

Genetic improvement potential. Crop and livestock reduction studies by necessity depend on assumptions about adaptive actions by farmers and ranchers. However, agriculture has proven to be highly adaptive in the past. A particularly high uncertainty is the ability of conventional breeding and biotechnology to keep pace with the crop plant and animal genetic improvements needed for adaptation to climate-induced biotic and abiotic stresses.

Assessment of confidence based on evidence

Although evidence includes studies of observed climate and weather impacts on agriculture, projections of future changes using climate and crop yield models and econometric models show varying results depending on the choice of crop and assumptions regarding water availability. For example, projections of 2050 California crop yields show reductions in field crop yields, based on assumptions of a 21% decline in agricultural water use, shifts away from water-intensive crops to high-value specialty crops, and development of a more economical means of transferring water from northern to southern California.[47] Other studies, using projections of a dry, warmer future for California, and an assumption that water will flow from lower- to higher-valued uses (such as urban water use), generated a 15% decrease in irrigated acreage and a shift from lower- to higher-valued crops.[49]

Because net reductions in the costs of water shortages depend on multiple institutional responses, it is difficult as yet to locate a best estimate of water transfers between zero and the upper bound. Water scarcity may also be a function of tradeoffs between economic returns from agricultural production and returns for selling off property or selling water to urban areas (for example, Imperial Valley transfers to San Diego).

Given the evidence base and remaining uncertainties, confidence is **high** in this key message.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Increased warming, drought, and insect outbreaks, all caused by or linked to climate change, have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.

Description of evidence base

Increased warming and drought are extensively described in the foundational Technical Input Report (TIR).[103] U.S. temperatures have increased and are expected to continue to rise (Ch. 2: Our Changing Climate, Key Message 3). There have been regional changes in droughts, and there are observed and projected changes in cold and heat waves and droughts (Ch. 2: Our Changing Climate, Key Message 7) for the nation. A study for the Southwest[17] discusses trends and scenarios in both cold waves and heat waves.

Analyses of weather station data from the Southwest have detected changes from 1950 to 2005 that favor wildfire, and statistical analyses have attributed the changes to anthropogenic climate change. The changes include increased temperatures,[3] reduced snowpack,[27] earlier spring warmth,[30] and streamflow.[10] These climate changes have increased background tree mortality rates from 1955 to 2007 in old-growth conifer forests in California, Colorado, Utah, and the northwestern states[7] and caused extensive piñon pine mortality in Arizona, Colorado, New Mexico, and Utah between 1989 and 2003.[69]

Climate factors contributed to increases in wildfire in the previous century. In mid-elevation conifer forests of the western United States, increases in spring and summer temperatures, earlier snowmelt, and longer summers increased fire frequency by 400% and burned area by 650% from 1970 to 2003.[8] Multivariate analysis of wildfire across the western U.S. from 1916 to 2003 indicates that climate was the dominant factor controlling burned area, even during periods of human fire suppression.[65] Reconstruction of fires of the past 400 to 3000 years in the western U.S.[66] and in Yosemite and Sequoia National Parks in California[67,68] confirm that temperature and drought are the dominant factors explaining fire occurrence.

Four different fire models project increases in fire frequency across extensive areas of the Southwest in this century.[71,72,73,74] Multivariate statistical generalized additive models[64,72] project extensive increases across the Southwest, but the models project decreases when assuming that climate alters patterns of net primary productivity. Logistic regressions[74] project increases across most of California, except for some southern parts of the state, with average fire frequency increasing 37% to 74%. Linear regression models project up to a doubling of burned area in the southern Rockies by 2070 under emissions scenarios B1 or A2.[73] The MC1 dynamic global vegetation model projects increases in fire frequencies on 40% of the area of the Southwest from 2000 to 2100 and decreases on 50% of the areas for emissions scenarios B1 and A2.[71]

Excessive wildfire destroys homes, exposes slopes to erosion and landslides, and threatens public health, causing economic damage.[59,60] Further impacts to communities and various economies (local, state, and national) have been projected.[74]

New information and remaining uncertainties

Uncertainties in future projections derive from the inability of models to accurately simulate all past fire patterns, and from the different GCMs, emissions scenarios, and spatial resolutions used by different fire model projections. Fire projections depend highly on the spatial and temporal distributions of precipitation projections, which vary widely across GCMs. Although models generally project future increases in wildfire, uncertainty remains on the exact locations. Research groups continue to refine the fire models.

Assessment of confidence based on evidence

There is **high** confidence in this key message given the extensive evidence base and discussed uncertainties.

Key message #4 Traceable Account

Flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some California coastal areas during storms and extreme high tides. Sea level rise is projected to increase as Earth continues to warm, resulting in major damage as wind-driven waves ride upon higher seas and reach farther inland.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report.[103] Several studies document potential coastal flooding, erosion, and wind-driven wave damages in coastal areas of California due to sea level rise (for example, Bromirski et al. 2012; Heberger et al. 2011, and Revell et al. 2011[81,82]). Global sea level has risen, and further rise of 1 to 4 feet is projected by 2100 (Ch. 2: Our Changing Climate, Key Message 10).

All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. In addition, numerous recent studies[78,80] produce much higher sea level rise projections for the rest of this century as compared to the projections in the most recent report of the Intergovernmental Panel on Climate Change[83] for the rest of this century.

New information and remaining uncertainties

There is strong recent evidence from satellites such as GRACE[110] and from direct observations that glaciers and ice caps worldwide are losing mass relatively rapidly, contributing to the recent increase in the observed rate of sea level rise.

Major uncertainties are associated with sea level rise projections, such as the behavior of ice sheets with global warming and the actual level of global warming that the Earth will experience in the future.[78,80] Regional sea level rise projections are even more uncertain than the projections for global averages because local factors such as the steric component (changes in the volume of water with changes in temperature and salinity) of sea level rise at regional levels and the vertical movement of land have large uncertainties.[78] However, it is virtually certain that sea levels will go up with a warming planet as demonstrated in the paleoclimatic record, modeling, and from basic physical arguments.

Assessment of confidence based on evidence

Given the evidence, especially since the last IPCC report,[83] there is **very high** confidence the sea level will continue to rise and that this will entail major damage to coastal regions in the Southwest. There is also **very high** confidence that flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some areas of the California coast during storms and extreme high tides.

Key message #5 Traceable Account

Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in southwestern cities, which are home to more than 90% of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.

Description of evidence base

There is excellent agreement regarding the urban heat island effect and exacerbation of heat island temperatures by increases in regional temperatures caused by climate change. There is abundant evidence of urban heat island effect for some Southwest cities (for example, Sheridan et al.[98]), as well as several studies, some from outside the region, of the public health threats of urban heat to residents (for example, Ch. 9: Human Health, Ostro et al. 2009, 2001[99,100]). Evidence includes observed urban heat island studies and modeling of future climates, including some climate change modeling studies for individual urban areas (for example, Phoenix and Los Angeles). There is wide agreement in Southwest states that increasing temperatures combined with projected population growth will stress urban water supplies and require continued water conservation and investment in new water supply options. There is substantial agreement that disruption to urban electricity may cause cascading impacts, such as loss of water, and that projected diminished supplies will pose challenges for urban cooling (for example, the need for supplemental irrigation for vegetation-based cooling). However, there are no studies on urban power disruption induced by climate change.

With projected surface water losses, and increasing water demand due to increasing temperatures and population, water supply in Southwest cities will require greater conservation efforts and capital investment in new water supply sources.[92] Several southwestern states, including California, New Mexico, and Colorado have begun to study climate impacts to water resources, including impacts in urban areas.[91]

The interdependence of infrastructure systems is well established, especially the dependence of systems on electricity and communications and control infrastructures, and the potential cascading effects of breakdowns in infrastructure systems.[16] The concentration of infrastructures in urban areas adds to the vulnerability of urban populations to infrastructure breakdowns. This has been documented in descriptions for major power outages such as the Northeast power blackout of 2003, or the recent September 2011 San Diego blackout.[94]

A few references point to the role of urban power outages in threatening public health due to loss of air conditioning[14] and disruption to water supplies.[94]

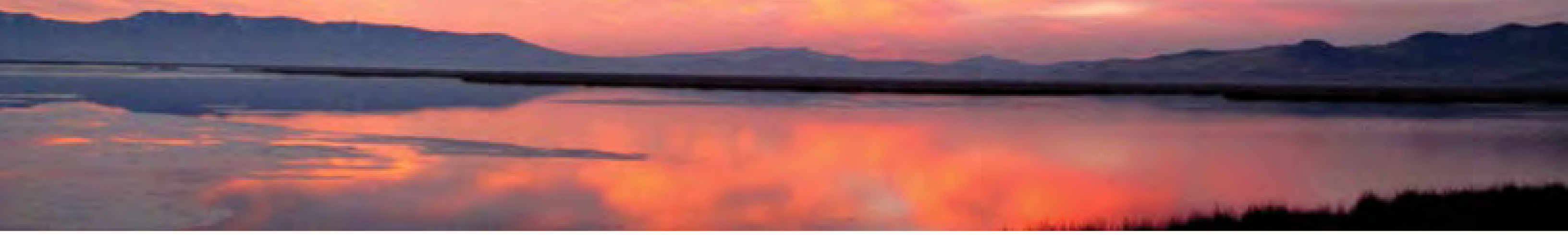
New information and remaining uncertainties

Key uncertainties include the intensity and spatial extent of drought and heat waves. Uncertainty is also associated with quantification of the impact of temperature and water availability on energy generation, transmission, distribution, and consumption – all of which have an impact on possible disruptions to urban electricity. Major disruptions are contingent on a lack of operator response and/or adaptive actions such as installation of adequate electricity-generating capacity to serve the expected enhanced peak electricity demand. Thus a further uncertainty is the extent to which adaptation actions are taken.

Assessment of confidence based on evidence

The urban heat island effect is well demonstrated and hence projected climate-induced increases to heat will increase exposure to heat-related illness. Electricity disruptions are a key uncertain factor, and potential reductions in water supply not only may reduce hydropower generation, but also availability of water for cooling of thermal power plants.

Based on the substantial evidence and the remaining uncertainties, confidence in each aspect of the key message is **high**.



Climate Change Impacts in the United States

CHAPTER 21
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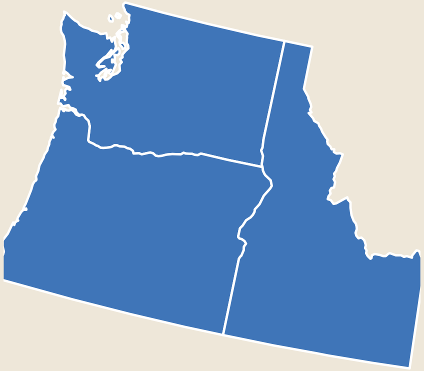

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21 NORTHWEST

KEY MESSAGES

1. **Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.**
2. **In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.**
3. **The combined impacts of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.**
4. **While the agriculture sector's technical ability to adapt to changing conditions can offset some adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.**

With craggy shorelines, volcanic mountains, and high sage deserts, the Northwest's complex and varied topography contributes to the region's rich climatic, geographic, social, and ecologic diversity. Abundant natural resources – timber, fisheries, productive soils, and plentiful water – remain important to the region's economy.

Snow accumulates in mountains, melting in spring to power both the region's rivers and economy, creating enough hydropower (40% of national total)[1] to export 2 to 6 million megawatt hours per month.[2] Snowmelt waters crops in the dry interior, helping the region produce tree fruit (number one in the world) and almost $17 billion worth of agricultural commodities, including 55% of potato, 15% of wheat, and 11% of milk production in the United States.[3]

Seasonal water patterns shape the life cycles of the region's flora and fauna, including iconic salmon and steelhead, and forested ecosystems, which cover 47% of the landscape.[4] Along more than 4,400 miles of coastline, regional economic centers are juxtaposed with diverse habitats and ecosystems that support thousands of species of fish and wildlife, including commercial fish and shellfish resources valued at $480 million in 2011.[5]

Adding to the influence of climate, human activities have altered natural habitats, threatened species, and extracted so much water that there are already conflicts among multiple users in dry years. More recently, efforts have multiplied to balance environmental restoration and economic growth while evaluating climate risks. As conflicts and tradeoffs increase, the region's population continues to grow, and the regional consequences of climate change continue to unfold. The need to seek solutions to these conflicts is becoming increasingly urgent.

The Northwest's economy, infrastructure, natural systems, public health, and vitally important agriculture sector all face important climate change related risks. Those risks – and possible adaptive responses – will vary significantly across the region.[6] Impacts on infrastructure, natural systems, human health, and economic sectors, combined with issues of social and ecological vulnerability, will play out quite differently in largely natural areas, like the Cascade Range or Crater Lake National Park, than in urban areas like Seattle and Portland (Ch. 11: Urban),[7] or among the region's many Native American tribes, like the Umatilla or the Quinault (Ch. 12: Indigenous Peoples).[8]

As climatic conditions diverge from those that determined patterns of development and resource use in the last century, and as demographic, economic, and technological changes also stress local systems, efforts to cope with climate change would benefit from an evolving, iterative risk management approach.[9]

Observed Climate Change

Temperatures increased across the region from 1895 to 2011, with a regionally averaged warming of about 1.3°F.[10] While precipitation has generally increased, trends are small as compared to natural variability. Both increasing and decreasing trends are observed among various locations, seasons, and time periods of analysis (Ch. 2: Our Changing Climate, Figure 2.12). Studies of observed changes in extreme precipitation use different time periods and definitions of "extreme," but none find statistically significant changes in the Northwest.[11] These and other climate trends include contributions from both human influences (chiefly heat-trapping gas emissions) and natural climate variability, and consequently are not projected to be uniform or smooth across the country or over time (Ch. 2: Our Changing Climate, Key Message 3). They are also consistent with expected changes due to human activities (Ch. 2: Our Changing Climate, Key Message 1).

Projected Climate Change

An increase in average annual temperature of 3.3°F to 9.7°F is projected by 2070 to 2099 (compared to the period 1970 to 1999), depending largely on total global emissions of heat-trapping gases. The increases are projected to be largest in summer. This chapter examines a range of scenarios, including ones where emissions increase and then decline, leading to lower (B1 and RCP 4.5) and medium (A1B) total emissions, and scenarios where emissions continue to rise with higher totals (A2, A1FI, and RCP 8.5 scenarios). Change in annual average precipitation in the Northwest is projected to be within a range of an 11% decrease to a 12% increase for 2030 to 2059 and a 10% decrease to an 18% increase for 2070 to 2099[12] for the B1, A1B, and A2 scenarios (Ch. 2: Our Changing Climate). For every season, some models project decreases and some project increases (Ch. 2: Our Changing Climate, Key Message 5),[10,12] yet one aspect of seasonal changes in precipitation is largely consistent across climate models: for scenarios of continued growth in global heat-trapping gas emissions, summer precipitation is projected to decrease by as much as 30% by the end of the century (Ch. 2: Our Changing Climate).[10,12] Northwest summers are already dry and although a 10% reduction (the average projected change for summer) is a small amount of precipitation, unusually dry summers have many noticeable consequences, including low streamflow west of the Cascades[13] and greater extent of wildfires throughout the region.[14] Note that while projected temperature increases are large relative to natural variability, the relatively small projected changes in precipitation are likely to be masked by natural variability for much of the century.[15]

Ongoing research on the implications of these and other changes largely confirms projections and analyses made over the last decade, while providing more information about how climate impacts are likely to vary from place to place within the region. In addition, new areas of concern, such as ocean acidification, have arisen.

Key Message 1: Water-related Challenges

Changes in the timing of streamflow related to changing snowmelt have been observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.

Description of Observed and Projected Changes

Observed regional warming has been linked to changes in the timing and amount of water availability in basins with significant snowmelt contributions to streamflow. Since around 1950, area-averaged snowpack on April 1 in the Cascade Mountains decreased about 20%,[16] spring snowmelt occurred 0 to 30 days earlier depending on location,[17] late winter/early spring streamflow increases ranged from 0% to greater than 20% as a fraction of annual flow,[18,19] and summer flow decreased 0% to 15% as a fraction of annual flow,[17] with exceptions in smaller areas and shorter time periods.[20]

Hydrologic response to climate change will depend upon the dominant form of precipitation in a particular watershed, as well as other local characteristics including elevation, aspect, geology, vegetation, and changing land use.[22] The largest responses are expected to occur in basins with significant snow accumulation, where warming increases winter flows and advances the timing of spring melt.[18,23] By 2050, snowmelt is pro-

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jected to shift three to four weeks earlier than the 20th century average, and summer flows are projected to be substantially lower, even for an emissions scenario that assumes substantial emissions reductions (B1).[24] In some North Cascade rivers, a significant fraction (10% to 30%) of late summer flow originates as glacier melt;[25] the consequences of eventual glacial disappearance are not well quantified. Basins with a significant groundwater component may be less responsive to climate change than indicated here.[26]

Changes in river-related flood risk depends on many factors, but warming is projected to increase flood risk the most in mixed basins (those with both winter rainfall and late spring snowmelt-related runoff peaks) and remain largely unchanged in snow-dominant basins.[27] Regional climate models project increases of 0% to 20% in extreme daily precipitation, depending on location and definition of "extreme" (for example, annual wettest day).

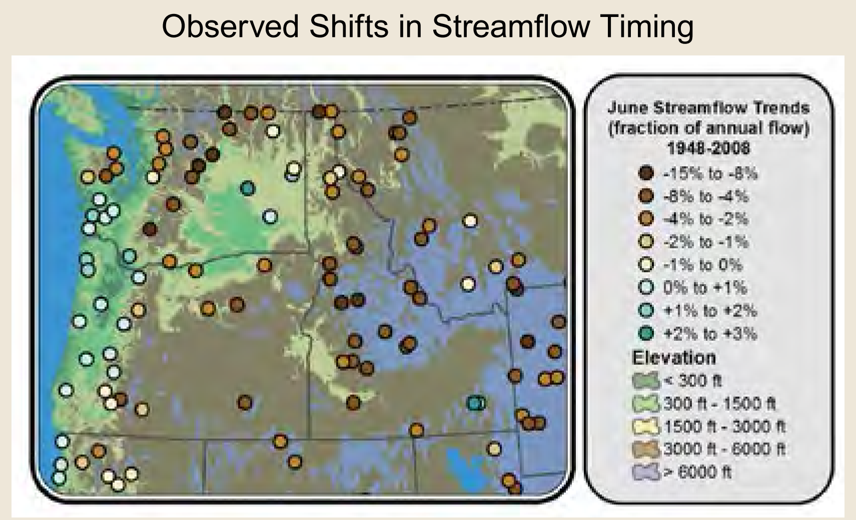
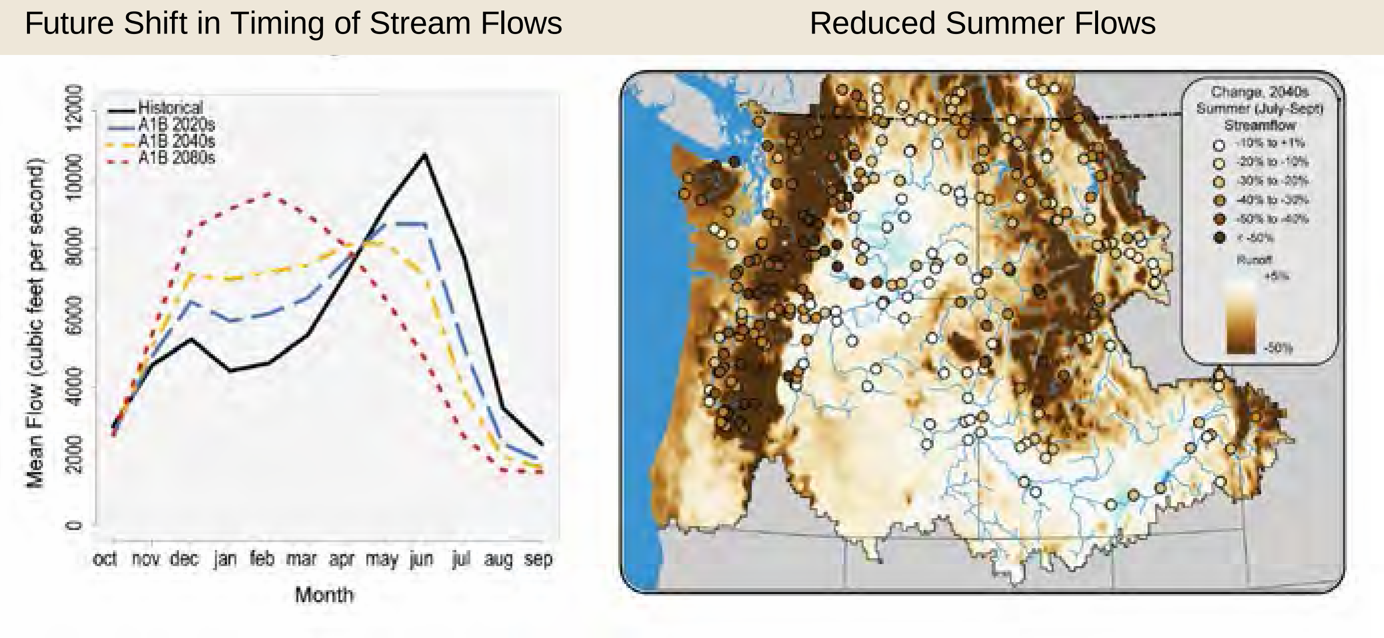

Observed Shifts in Streamflow Timing

Figure 21.1. Reduced June flows in many Northwest snow-fed rivers is a signature of warming in basins that have a significant snowmelt contribution. The fraction of annual flow occurring in June increased slightly in rain-dominated coastal basins and decreased in mixed rain-snow basins and snowmelt-dominated basins over the period 1948 to 2008.[21] The high flow period is in June for most Northwest river basins; decreases in summer flows can make it more difficult to meet a variety of competing human and natural demands for water. (Figure source: adapted from Fritze et al. 2011[21]).


Future Shift in Timing of Stream Flows

Reduced Summer Flows

Figure 21.2. (Left) Projected increased winter flows and decreased summer flows in many Northwest rivers will cause widespread impacts. Mixed rain-snow watersheds, such as the Yakima River basin, an important agricultural area in eastern Washington, will see increased winter flows, earlier spring peak flows, and decreased summer flows in a warming climate. Changes in average monthly streamflow by the 2020s, 2040s, and 2080s (as compared to the period 1916 to 2006) indicate that the Yakima River basin could change from a snow-dominant to a rain-dominant basin by the 2080s under the A1B emissions scenario (with eventual reductions from current rising emissions trends). (Figure source: adapted from Elsner et al. 2010)[24].

(Right) Natural surface water availability during the already dry late summer period is projected to decrease across most of the Northwest. The map shows projected changes in local runoff (shading) and streamflow (colored circles) for the 2040s (compared to the period 1915 to 2006) under the same scenario as the left figure (A1B).[29] Streamflow reductions such as these would stress freshwater fish species (for instance, endangered salmon and bull trout) and necessitate increasing tradeoffs among conflicting uses of summer water. Watersheds with significant groundwater contributions to summer streamflow may be less responsive to climate change than indicated here.[26]

Averaged over the region, the number of days with more than one inch of precipitation is projected to increase 13% in 2041 to 2070 compared with 1971 to 2000 under a scenario that assumes a continuation of current rising emissions trends (A2),[10] though these projections are not consistent across models.[28] This increase in heavy downpours could increase flood risk in mixed rain-snow and rain-dominant basins, and could also increase stormwater management challenges in urban areas.

Consequences and Likelihoods of Changes

Reservoir systems have multiple objectives, including irrigation, municipal and industrial use, hydropower production, flood control, and preservation of habitat for aquatic species. Modeling studies indicate, with near 100% likelihood and for all emissions scenarios, that reductions in summer flow will occur by 2050 in basins with significant snowmelt (for example, Elsner et al. 2010[24]). These reduced flows will require more tradeoffs among objectives of the whole system of reservoirs,[30] especially with the added challenges of summer increases in electric power demand for cooling[31] and additional water consumption by crops and forests.[10,32] For example, reductions in hydropower production of as much as 20% by the 2080s could be required to preserve in-stream flow targets for fish in the Columbia River basin.[33] Springtime irrigation diversions increased between 1970 and 2007 in the Snake River basin, as earlier snowmelt led to reduced spring soil moisture.[34] In the absence of human adaptation, annual hydropower production is much more likely to decrease than to increase in the Columbia River basin; economic impacts of hydropower changes could be hundreds of millions of dollars per year.[35]


NOAA

Region-wide summer temperature increases and, in certain basins, increased river flooding and winter flows and decreased summer flows, will threaten many freshwater species, particularly salmon, steelhead, and trout.[27] Rising temperatures will increase disease and/or mortality in several iconic salmon species, especially for spring/summer Chinook and sockeye in the interior Columbia and Snake River basins.[36] Some Northwest streams[30] and lakes have already warmed over the past three decades, contributing to changes such as earlier Columbia River sockeye salmon migration[37] and earlier blooms of algae in Lake Washington.[38] Relative to the rest of the United States, Northwest streams dominated by snowmelt runoff appear to be less sensitive, in the short term, to warming due to the temperature buffering provided by snowmelt and groundwater contributions to those streams.[39] However, as snowpack declines, the future sensitivity to warming is likely to increase in these areas.[40] By the 2080s, suitable habitat for the four trout species of the interior western U.S. is projected to decline 47% on average, compared to the period 1978-1997.[41] As species respond to climate change in diverse ways, there is potential for ecological mismatches to occur – such as in the timing of the emergence of predators and their prey.[38]

Adaptive Capacity and Implications for Vulnerability

The ability to adapt to climate changes is strengthened by extensive water resources infrastructure, diversity of institutional arrangements,[42] and management agencies that are responsive to scientific input. However, over-allocation of existing water supply, conflicting objectives, limited management flexibility caused by rigid water allocation and operating rules, and other institutional barriers to changing operations continue to limit progress towards adaptation in many parts of the Columbia River basin.[43,44] Vulnerability to projected changes in snowmelt timing is probably highest in basins with the largest hydrologic response to warming and lowest management flexibility – that is, fully allocated, mid-elevation, temperature-sensitive, mixed rain-snow watersheds with existing conflicts among users of summer water. Regional power planners have expressed concerns over the existing hydroelectric system's potential inability to provide adequate summer electricity given the combination of climate change, demand growth, and operating constraints.[1] Vulnerability is probably lowest where hydrologic change is likely to be smallest (in rain-dominant basins) and where institutional arrangements are simple and current natural and human demands rarely exceed current water availability.[43,45,46]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The adaptive capacity of freshwater ecosystems also varies and, in managed basins, will depend on the degree to which the need to maintain streamflows and water quality for fish and wildlife is balanced with human uses of water resources. In highly managed rivers, release of deeper, colder water from reservoirs could offer one of the few direct strategies to lower water temperatures downstream.[47] Actions to improve stream habitat, including planting trees for shade, are being tested. Some species may be able to change behavior or take advantage of cold-water refuges.[48]

Key Message 2: Coastal Vulnerabilities

In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.

With diverse landforms (such as beaches, rocky shorelines, bluffs, and estuaries), coastal and marine ecosystems, and human uses (such as rural communities, dense urban areas, international ports, and transportation), the Northwest coast will experience a wide range of climate impacts.

Description of Observed and Projected Changes

Global sea levels have risen about 8 inches since 1880 and are projected to rise another 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 10). Many local and regional factors can modify the global trend, including vertical land movement, oceanic winds and circulation, sediment compaction, subterranean fluid withdrawal (such as groundwater and natural gas), and other geophysical factors such as the gravitational effects of major ice sheets and glaciers on regional ocean levels.


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Much of the Northwest coastline is rising due to a geophysical force known as “tectonic uplift,” which raises the land surface. Because of this, apparent sea level rise is less than the currently observed global average. However, a major earthquake along the Cascadia subduction zone, expected within the next few hundred years, would immediately reverse centuries of uplift and, based on historical evidence, increase relative sea level 40 inches or more.[49,50] On the other hand, some Puget Sound locations are currently experiencing subsidence (where land is sinking or settling) and could see the reverse effect, witnessing immediate uplift during a major earthquake and lowered relative sea levels.[51,52]

Taking into account many of these factors and considering a wider range of emissions scenarios than are used in this assessment (Appendix 5: Scenarios and Models), a recent

Projected Relative Sea Level Rise for the Latitude of Newport, Oregon

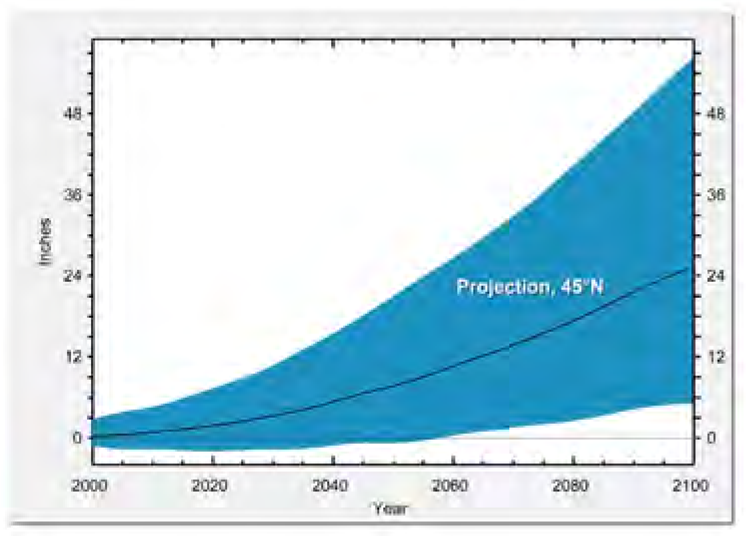

Figure 21.3. Projected relative sea level rise for the latitude of Newport, Oregon (relative to the year 2000) is based on a broader suite of emissions scenarios (ranging from B1 to A1FI) and a more detailed and regionally-focused calculation than those generally used in this assessment (see Ch. 2: Our Changing Climate).[50] The blue area shows the range of relative sea level rise, and the black line shows the projection, which incorporates global and regional effects of warming oceans, melting land ice, and vertical land movements.[50] Given the difficulty of assigning likelihood to any one possible trajectory of sea level rise at this time, a reasonable risk assessment would consider multiple scenarios within the full range of possible outcomes shown, in conjunction with long- and short-term compounding effects, such as El Niño-related variability and storm surge. (Data from NRC 2012[50]).

evaluation calculated projected sea level rise and ranges for the years 2030, 2050, and 2100 (relative to 2000) based on latitude for Washington, Oregon, and California (see Figure 21.3).[50] In addition to long-term climate-driven changes in sea level projected for the Northwest, shorter-term El Niño conditions can increase regional sea level by about 4 to 12 inches for periods of many months.[50,53]

Northwest coastal waters, some of the most productive on the West Coast,[54] have highly variable physical and ecological conditions as a result of seasonal and year-to-year changes in upwelling of deeper marine water that make longer-term changes difficult to detect. Coastal sea surface temperatures have increased[55] and summertime fog has declined between 1900 and the early 2000s, both of which could be consequences of weaker upwelling winds.[56] Projected changes include increasing but highly variable acidity,[57,58,59] increasing surface water temperature (2.2°F from the period 1970 to 1999 to the period 2030 to 2059),[60] and possibly changing storminess.[61] Climate models show inconsistent projections for the future of Northwest coastal upwelling.[12,62]

Consequences and Likelihoods of Changes

In Washington and Oregon, more than 140,000 acres of coastal lands lie within 3.3 feet in elevation of high tide.[63] As sea levels continue to rise, these areas will be inundated more frequently. Many coastal wetlands, tidal flats, and beaches will probably decline in quality and extent as a result of sea level rise, particularly where habitats cannot shift inland because of topographical limitations or physical barriers resulting from human development. Species such as shorebirds and forage fish (small fish eaten by larger fish, birds, or mammals) would be harmed, and coastal infrastructure and communities would be at greater risk from coastal storms.[64]

Ocean acidification threatens culturally and commercially significant marine species directly affected by changes in ocean chemistry (such as oysters) and those affected by changes in the marine food web (such as Pacific salmon[65]). Northwest coastal waters are among the most acidified worldwide, especially in spring and summer with coastal upwelling[58,59,66] combined with local factors in estuaries.[57,58]

Increasing coastal water temperatures and changing ecological conditions may alter the ranges, types, and abundances of marine species.[67,68] Recent warm periods in the coastal ocean, for example, saw the arrival of subtropical and offshore marine species from zooplankton to top predators such as striped marlin, tuna, and yellowtail more common to the Baja area.[69] Warmer water in regional estuaries (such as Puget Sound) may contribute to a higher incidence of harmful blooms of algae linked to paralytic shellfish poisoning,[70] and may result in adverse economic impacts from beach closures affecting recreational harvesting of shellfish such as razor clams.[71] Toxicity of some harmful algae appears to be increased by acidification.[72]

Rising Sea Levels and Changing Flood Risks in Seattle

Figure 21.4. Areas of Seattle projected by Seattle Public Utilities to be below sea level during high tide (Mean Higher High Water) and therefore at risk of flooding or inundation are shaded in blue under three levels of sea level rise,[78] assuming no adaptation. (High [50 inches] and medium [13 inches] levels are within the range projected for the Northwest by 2100; the highest level [88 inches] includes the compounding effect of storm surge, derived from the highest observed historical tide in Seattle[79]). Unconnected inland areas shown to be below sea level may not be inundated, but could experience problems due to areas of standing water caused by a rise in the water table and drainage pipes backed up with seawater. (Figure source: Seattle Public Utilities[80]).

Many human uses of the coast – for living, working, and recreating – will also be negatively affected by the physical and ecological consequences of climate change. Erosion, inundation, and flooding will threaten public and private property along the coast; infrastructure, including wastewater treatment plants;[7,73] stormwater outfalls;[74,75] ferry terminals;[76] and coastal road and rail transportation, especially in Puget Sound.[77] Municipalities from Seattle[74] and Olympia,[75] Washington, to Neskowin, Oregon, have mapped risks from the combined effects of sea level rise and other factors.

Adaptive Capacity and Implications for Vulnerability

Human activities have increased the vulnerability of many coastal ecosystems, by degrading and eliminating habitat[81] and by building structures that, along with natural bluffs, thwart inland movement of many remaining habitats. In Puget Sound, for example, seawalls, bulkheads, and other structures have modified an estimated one-third of the shoreline,[82] though some restoration has occurred. Human responses to erosion and sea level rise, especially shoreline armoring, will largely determine the viability of many shallow-water and estuarine ecosystems.[68,82,83] In communities with few alternatives to existing coastal transportation networks, such as on parts of Highway 101 in Oregon, sea level rise and storm surges will pose an increasing threat to local commerce and livelihoods. Finally, there are few proven options for ameliorating projected ocean acidification.[84]

Adapting the Nisqually River Delta to Sea Level Rise

Figure 21.5. In Washington's Nisqually River Delta, estuary restoration on a large scale to assist salmon and wildlife recovery provides an example of adaptation to climate change and sea level rise. After a century of isolation behind dikes (left), much of the Nisqually National Wildlife Refuge was reconnected with tidal flow in 2009 by removal of a major dike and restoration of 762 acres (right), with the assistance of Ducks Unlimited and the Nisqually Indian Tribe. This reconnected more than 21 miles of historical tidal channels and floodplains with Puget Sound.[85] A new exterior dike was constructed to protect freshwater wetland habitat for migratory birds from tidal inundation and future sea level rise. Combined with expansion of the authorized Refuge boundary, ongoing acquisition efforts to expand the Refuge will enhance the ability to provide diverse estuary and freshwater habitats despite rising sea level, increasing river floods, and loss of estuarine habitat elsewhere in Puget Sound. This project is considered a major step in increasing estuary habitat and recovering the greater Puget Sound estuary. (Photo credits: (left) Jesse Barham, U.S. Fish and Wildlife Service; (right) Jean Takekawa, U.S. Fish and Wildlife Service).

Key Message 3: Impacts on Forests

The combined impacts of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.

Evergreen coniferous forests are a prominent feature of Northwest landscapes, particularly in mountainous areas. Forests support diverse fish and wildlife species, promote clean air and water, stabilize soils, and store carbon. They support local economies and traditional tribal uses and provide recreational opportunities.

Description of Observed and Projected Changes

Climate change will alter Northwest forests by increasing wildfire risk and insect and tree disease outbreaks, and by forcing longer-term shifts in forest types and species (see Ch 7: Forests). Many impacts will be driven by water deficits, which increase tree stress and mortality, tree vulnerability to insects, and fuel flammability. The cumulative effects of disturbance – and possibly interactions between insects and fires – will cause the greatest changes in Northwest forests.[86,87] A similar outlook is expected for the Southwest region (see Ch. 20: Southwest, Key Message 3).

Forest Mortality

Figure 21.6. Forest mortality due to fire and insect activity is already evident in the Northwest. Continued changes in climate in coming decades are expected to increase these effects. Trees killed by a fire (left side of watershed) and trees killed by mountain pine beetle and spruce beetle infestations (orange and gray patches, right side of watershed) in subalpine forest in the Pasayten Wilderness, Okanogan Wenatchee National Forest, Washington, illustrates how cumulative disturbances can affect forests. (Photo credit: Jeremy Littell, USGS).

Although wildfires are a natural part of most Northwest forest ecosystems, warmer and drier conditions have helped increase the number and extent of wildfires in western U.S. forests since the 1970s.[14,87,88,89] This trend is expected to continue under future climate conditions. By the 2080s, the median annual area burned in the Northwest would quadruple relative to the 1916 to 2007 period to 2 million acres (range of 0.2 to 9.8 million acres) under the A1B scenario. Averaged over the region, this would increase the probability that 2.2 million acres would burn in a year from 5% to nearly 50%.[14] Within the region, this probability will vary substantially with sensitivity of fuels to climatic conditions and local variability in fuel type and amount, which are in turn a product of forest type, effectiveness of fire suppression, and land use. For example, in the Western Cascades, the year-to-year variability in area burned is difficult to attribute to climate conditions, while fire in the eastern Cascades and other specific vegetation zones is responsive to climate.[14] How individual fires behave in the future and what impacts they have will depend on factors we cannot yet project, such as extreme daily weather and forest fuel conditions.

Higher temperatures and drought stress are contributing to outbreaks of mountain pine beetles that are increasing pine mortality in drier Northwest forests.[90,91] This trend is projected to continue with ongoing warming.[14,92,93,94] Between now and the end of this century, the elevation of suitable beetle habitat is projected to increase as temperature increases, exposing higher-elevation forests to the pine beetle, but ultimately limiting available area as temperatures exceed the beetles' optimal temperatures.[14,92,93] As a result, the proportion of Northwest pine forests where mountain pine beetles are most likely to survive is projected to first increase (27% higher in 2001 to 2030 compared to 1961 to 1990) and then decrease (about 49% to 58% lower by 2071 to 2100).[92] For many tree species, the most climatically suited areas will shift from their current locations, increasing vulnerability to insects, disease, and fire in areas that become unsuitable. Eighty-five percent of the current range of three species that are host to pine beetles is projected to be climatically unsuitable for one or more of those species by the 2060s,[14,95] while 21 to 38 currently existing plant species may no longer find climatically appropriate habitat in the Northwest by late this century.[96]

Consequences and Likelihoods of Changes

The likelihood of increased disturbance (fire, insects, diseases, and other sources of mortality) and altered forest distribution are very high in areas dominated by natural vegetation, and the resultant changes in habitat would affect native species and ecosystems. Subalpine forests and alpine ecosystems are especially at risk and may undergo almost complete conversion to other vegetation types by the 2080s (A2 and B1;[104] A2;[105] Ensemble A2, B1, B2;[106]). While increased area burned can be statistically estimated from climate projections, changes in the risk of very large, high-intensity, stand-replacing fires cannot yet be predicted, but such events could have enormous impacts for forest-dependent species.[88] Increased wildfire could exacerbate respiratory and cardiovascular illnesses in nearby populations due to smoke and particulate pollution (Ch. 9: Human Health).[107,108]

These projected forest changes will have moderate economic impacts for the region as a whole, but could significantly affect local timber revenues and bioenergy markets.[109]

Insects and Fire in Northwest Forests

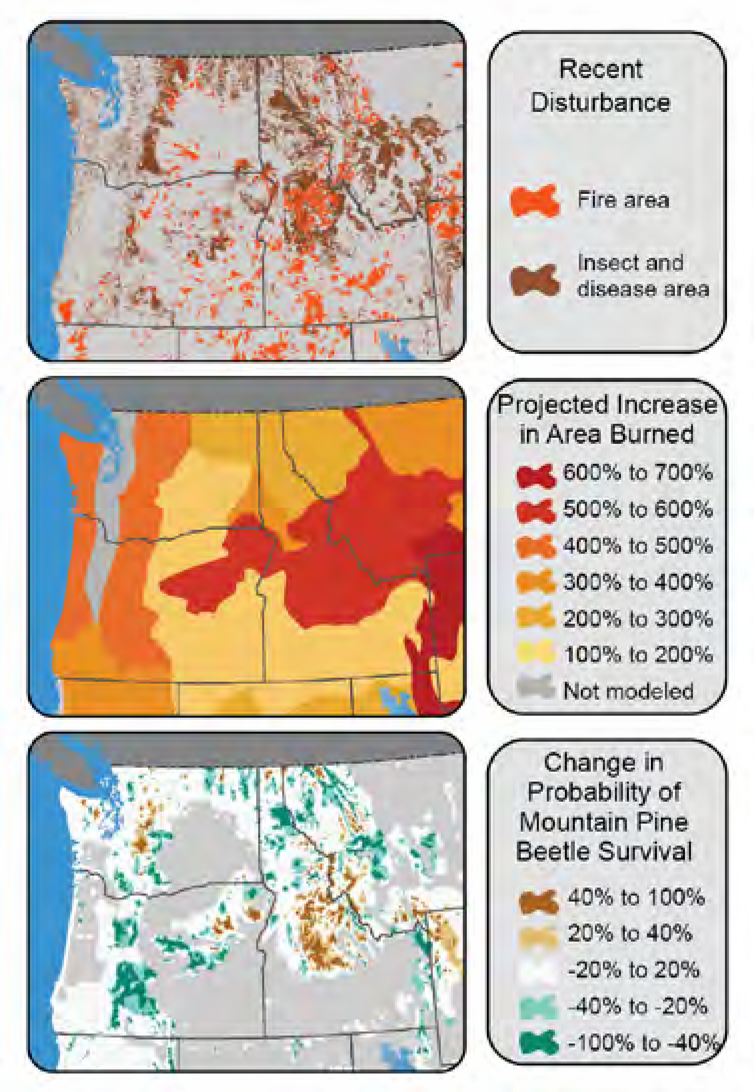

Figure 21.7.

(Top) Insects and fire have cumulatively affected large areas of the Northwest and are projected to be the dominant drivers of forest change in the near future. Map shows areas recently burned (1984 to 2008)[97,98] or affected by insects or disease (1997 to 2008).[99]

(Middle) Map indicates the increases in area burned that would result from the regional temperature and precipitation changes associated with a 2.2°F global warming[100] across areas that share broad climatic and vegetation characteristics.[101] Local impacts will vary greatly within these broad areas with sensitivity of fuels to climate.[14]

(Bottom) Projected changes in the probability of climatic suitability for mountain pine beetles for the period 2001 to 2030 (relative to 1961 to 1990), where brown indicates areas where pine beetles are projected to increase in the future and green indicates areas where pine beetles are expected to decrease in the future. Changes in probability of survival are based on climate-dependent factors important in beetle population success, including cold tolerance,[102] spring precipitation,[103] and seasonal heat accumulation.[91,92]

Adaptive Capacity and Implications for Vulnerability

Ability to prepare for these changes varies with land ownership and management priorities. Adaptation actions that decrease forest vulnerability exist, but none is appropriate across all of the Northwest's diverse climate threats, land-use histories, and management objectives.[86,110] Surface and canopy thinning can reduce the occurrence and effects of high severity fire in currently low severity fire systems, like drier eastern Cascades forests,[111] but may be ineffective in historically high-severity-fire forests, like the western Cascades, Olympics, and some subalpine forests. It is possible to use thinning to reduce tree mortality from insect outbreaks,[86,112] but not on the scale of the current outbreaks in much of the West.

Key Message 4: Adapting Agriculture

While the agriculture sector's technical ability to adapt to changing conditions can offset some adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.

Agriculture provides the economic and cultural foundation for Northwest rural populations and contributes substantively to the overall economy. Agricultural commodities and food production systems contributed 3% and 11% of the region's gross domestic product, respectively, in 2009.[113] Although the overall consequences of climate change will probably be lower in the Northwest than in certain other regions, sustainability of some Northwest agricultural sectors is threatened by soil erosion[114] and water supply uncertainty, both of which could be exacerbated by climate change.

Description of Observed and Projected Changes

Northwest agriculture's sensitivity to climate change stems from its dependence on irrigation water, a specific range of temperatures, precipitation, and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming will reduce the availability of irrigation water in snowmelt-fed basins and increase the probability of heat stress to field crops and tree fruit. Some crops will benefit from a longer growing season[115] and/or higher atmospheric carbon dioxide, at least for a few decades.[115,116] Longer-term consequences are less certain. Changes in plant diseases, pests, and weeds present additional potential risks. Higher average temperatures generally can exacerbate pest pressure through expanded geographic ranges, earlier emergence or arrival, and increased numbers of pest generations (for example, Ch. 6: Agriculture).[117] Specifics differ among pathogen and pest species and depend upon multiple interactions (Ch. 6: Agriculture)[118] preventing region-wide generalizations. Research is needed to project changes in vulnerabilities to pest, disease, and weed complexes for specific cropping systems in the Northwest.

Consequences of Changes

Because much of the Northwest has low annual precipitation, many crops require irrigation. Reduction in summer flows in snow-fed rivers (see Figure 21.2), coupled with warming that could increase agricultural and other demands, potentially produces irrigation water shortages.[108] The risk of a water-short year – when Yakima basin junior water rights holders are allowed only 75% of their water right amount – is projected to increase from 14% in the late 20th century to 32% by 2020 and 77% by 2080, assuming no adaptation and under the A1B scenario.[46]

Assuming adequate nutrients and excluding effects of pests, weeds, and diseases, projected increases in average temperature and hot weather episodes and decreases in summer soil moisture would reduce yields of spring and winter wheat in rain-fed production zones of Washington State by the end of this century by as much as 25% relative to 1975 to 2005. However, carbon dioxide fertilization should offset these effects, producing net yield increases as great as 33% by 2080.[115] Similarly, for irrigated potatoes in Washington State, carbon dioxide fertilization is projected to mostly offset direct climate change related yield losses, although yields are still projected to decline by 2% to 3% under the A1B emissions scenario.[115] Higher temperatures could also reduce potato tuber quality.[119]

Irrigated apple production is projected to increase in Washington State by 6% in the 2020s, 9% in the 2040s, and 16% in the 2080s (relative to 1975 to 2005) when offsetting effects of carbon dioxide fertilization are included.[115] However, because tree fruit requires chilling to ensure uniform flowering and fruit set and wine grape varieties have specific chilling requirements for maturation,[120] warming could adversely affect currently grown varieties of these commodities. Most published projections of climate change impacts on Northwest agriculture are limited to Washington State and have focused on major commodities, although more than 300 crops are grown in the region. More studies are needed to identify the implications of climate change for additional cropping systems and locations within the region. The economic consequences for Northwest agriculture will be influenced by input and output prices driven by global economic conditions as well as by regional and local changes in productivity.

Adaptive Capacity and Implications for Vulnerability

Of the four areas of concern discussed here, agriculture is perhaps best positioned to adapt to climate trends without explicit planning and policy, because it already responds to annual climate variations and exploits a wide range of existing climates across the landscape.[121] Some projected changes in climate, including warmer winters, longer annual frost-free periods, and relatively unchanged or increased winter precipitation, could be beneficial to some agriculture systems. Nonetheless, rapid climate change could present difficulties. Adaptation could occur slowly if substantial investments or significant changes in farm operations and equipment are required. Shifts to new varieties of wine grapes and tree fruit, if indicated, and even if ultimately more profitable, are necessarily slow and expensive. Breeding for drought- and heat-resistance requires long-term effort. Irrigation water shortages that necessitate shifts away from more profitable commodities could exact economic penalties.[108]

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The authors and several dozen collaborators undertook a risk evaluation of the impacts of climate change in the Northwest that informed the development of the four key messages in this chapter (see also Ch. 26: Decision Support). This process considered the combination of impact likelihood and the consequences for the region's economy, infrastructure, natural systems, human health, and the economically-important and climate sensitive regional agriculture sector (see Dalton et al. 2013[6] for details). The qualitative comparative risk assessment underlying the key messages in the Northwest chapter was informed by the Northwest Regional Climate Risk Framing workshop (December 2, 2011, in Portland, OR). The workshop brought together stakeholders and scientists from a cross-section of sectors and jurisdictions within the region to discuss and rank the likelihood and consequences for key climate risks facing the Northwest region and previously identified in the Oregon Climate Change Adaptation Framework.[122] The approach consisted of an initial qualitative likelihood assessment based on expert judgment and consequence ratings based on the conclusions of a group of experts and assessed for four categories: human health, economy, infrastructure, and natural systems.[123]

This initial risk exercise was continued by the lead author team of the Northwest chapter, resulting in several white papers that were 1) condensed and synthesized into the Northwest chapter, and 2) expanded into a book-length report on Northwest impacts.[6] The NCA Northwest chapter author team engaged in multiple technical discussions via regular teleconferences and two all-day meetings. These included careful review of the foundational technical input report[123] and approximately 80 additional technical inputs provided to the NCA by the public, as well additional published literature. They also drew heavily from two state climate assessment reports.[124]

The author team identified potential regional impacts by 1) working forward from drivers of regional climate impacts (for example, changes in temperature, precipitation, sea level, ocean chemistry, and storms), and 2) working backward from affected regional sectors (for example, agriculture, natural systems, and energy). The team identified and ranked the relative consequences of each impact for the region's economy, infrastructure, natural systems, and the health of Northwest residents. The likelihood of each impact was also qualitatively ranked, allowing identification of the impacts posing the highest risk, that is, likelihood × consequence, to the region as a whole. The key regionally consequential risks thus identified are those deriving from projected changes in streamflow timing (in particular, warming-related impacts in watersheds where snowmelt is an important contributor to flow); coastal consequences of the combined impact of sea level rise and other climate-related drivers; and changes in Northwest forest ecosystems. The Northwest chapter therefore focuses on the implications of these risks for Northwest water resources, key aquatic species, coastal systems, and forest ecosystems, as well as climate impacts on the regionally important, climate-sensitive agricultural sector.

Each author produced a white paper synthesizing the findings in his/her sectoral area, and a number of key messages pertaining to climate impacts in that area. These syntheses were followed by expert deliberation of draft key messages by the authors wherein each key message was defended before the entire author team before this key message was selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities," including likelihood of climate change and relative magnitude of its consequences for the region as a whole, including consequences for the region's economy, human health, ecosystems, and infrastructure.[123]

Though the risks evaluated were aggregated over the whole region, it was recognized that impacts, risks, and appropriate adaptive responses vary significantly in local settings. For all sectors, the focus on risks of importance to the region's overall economy, ecology, built environment, and health is complemented, where space allows, by discussion of the local specificity of climate impacts, vulnerabilities and adaptive responses that results from the heterogeneity of Northwest physical conditions, ecosystems, human institutions and patterns of resource use.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many

competing demands and causing far-reaching ecological and socioeconomic consequences.

Description of evidence base

This message was selected because of the centrality of the water cycle to many important human and natural systems of the Northwest: hydropower production and the users of this relatively inexpensive electricity; agriculture and the communities and economies dependent thereon, and; coldwater fish, including several species of threatened and endangered salmon, the tribal and fishing communities and ecosystems that depend on them, and the adjustments in human activities and efforts necessary to restore and protect them. Impacts of water-cycle changes on these systems, and any societal adjustments to them, will have far-reaching ecological and socioeconomic consequences.

Evidence that winter snow accumulation will decline under projected climate change is based on 20th century observations and theoretical studies of the sensitivity of Northwest snowpack to changes in precipitation and temperature. There is good agreement on the physical role of climate in snowpack development, and projections of the sign of future trends are consistent (many studies). However, climate variability creates disagreement over the magnitude of current and near-term future trends.

Evidence that projected climate change would shift the timing and amount of streamflow deriving from snowmelt is based on 20th century observations of climate and streamflow and is also based on hydrologic model simulation of streamflow responses to climate variability and change. There is good agreement on the sign of trends (many studies), though the magnitude of current and near-term future trends is less certain because of climate variability.

Evidence that declining snowpack and changes in the timing of snowmelt-driven streamflow will reduce water supply for many competing and time-sensitive demands is based on:

- hydrologic simulations, driven by future climate projections, that consistently show reductions in spring and summer flows in mixed rain-snow and some snow-dominant watersheds;
- documented competition among existing water uses (irrigation, power, municipal, and in-stream flows) and inability for all water systems to meet all summer water needs all of the time, especially during drier years;
- empirical and theoretical studies that indicate increased water demand for many uses under climate change; and
- policy and institutional analyses of the complex legal and institutional arrangements governing Northwest water management and the challenges associated with adjusting water management in response to changing conditions.

Evidence for far-reaching ecological and socioeconomic consequences of the above is based on:

- model simulations showing negative impacts of projected climate and altered streamflow on many water resource uses at scales ranging from individual basins (for example, Skagit, Yakima) to the region (for example, Columbia River basin);
- model simulations of future agricultural water allocation in the Yakima[46] and the Snake River Basin,[32] showing increased likelihood of water curtailments for junior water rights holders;
- model and empirical studies documenting sensitivity of coldwater fish to water temperatures, sensitivity of water temperature to air temperature, and projected warming of summer stream temperatures;
- regional and extra-regional dependence on Northwest-produced hydropower; and
- legal requirements to manage water resources for threatened & endangered fish as well as for human uses.

Evidence that water users in managed mixed rain-snow basins are likely to be the most vulnerable to climate change and less vulnerable in rain-dominated basins is based on:

- observed, theoretical, and simulated sensitivity of watershed hydrologic response to warming by basin type;
- historical observations and modeled simulations of tradeoffs required among water management objectives under specific climatic conditions;
- analyses from water management agencies of potential system impacts and adaptive responses to projected future climate; and
- institutional and policy analyses documenting sources and types of management rigidity (for example, difficulty adjusting management practices to account for changing conditions).

New information and remaining uncertainties

A key uncertainty is the degree to which current and future interannual and interdecadal variations in climate will enhance or obscure long-term anthropogenic climate trends.

Uncertainty over local groundwater or glacial inputs and other local effects may cause overestimates of increased stream temperature based solely on air temperature. However, including projected decreases in summer streamflow would increase estimates of summer stream temperature increases above those based solely on air temperature.

Uncertainty in how much increasing temperatures will affect crop evapotranspiration affects future estimates of irrigation demand.

Uncertainty in future population growth and changing per capita water use affects estimates of future municipal demand and therefore assessments of future reliability of water resource systems.

A major uncertainty is the degree to which water resources management operations of regulated systems can be adjusted to account for climate-driven changes in the amount and timing of streamflow, and how competing resource objectives will be accommodated or prioritized. Based on current institutional inertia, significant changes are unlikely to occur for several decades.

There is uncertainty in economic assessment of the impacts of hydrologic changes on the Northwest because much of the needed modeling and analysis is incomplete. Economic impacts assessment would require quantifying both potential behavioral responses to future climate-affected economic variables (prices of inputs and products) and to climate change itself. Some studies have sidestepped the issue of behavioral response to these and projected economic impacts based on future scenarios that do not consider adaptation, which lead to high estimates of "costs" or impacts.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Confidence is **very high** based on strong strength of evidence and **high** level of agreement among experts.

See specifics under "description of evidence" above.

KEY MESSAGE #2 TRACEABLE ACCOUNT

In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.

Description of evidence base

Given the extent of the coastline, the importance of coastal systems to the region's ecology, economy, and identity, and the difficulty of adapting in response, the consequences of sea level rise, ocean acidification, and other climate driven changes in ocean conditions and coastal weather are expected to be significant and largely negative, which is why this message was included.

Evidence for observed global (eustatic) sea level rise and regional sea level change derives from satellite altimetry and coastal tide gauges. Evidence for projected global sea level rise is described in Ch. 2: Our Changing Climate, in the recent NRC report[50] that includes a detailed discussion of the U.S. West Coast, and Parris et al. 2012.[125]

Evidence of erosion associated with coastal storms is based on observations of storm damage in some areas of the Northwest.

Evidence for erosion and inundation associated with projected sea level rise is based on observations and mapping of coastal elevations and geospatial analyses of the extent and location of inundation associated with various sea level rise and storm surge scenarios.

Evidence for climate change impacts on coastal infrastructure derives from geospatial analyses (mapping infrastructure locations likely to be affected by various sea level rise scenarios, storm surge scenarios and/or river flooding scenario), such as those undertaken by various local governments to assess local risks of flooding for the downtown area (Olympia), of sea level rise and storm surge for marine shoreline inundation and risk to public utility infrastructure (Seattle – highest observed tide from NOAA tide gauge added to projected sea levels), and of sea level rise for wastewater treatment plants and associated infrastructure (King County). Vulnerability of coastal transportation infrastructure to climate change has been assessed by combining geospatial risk analyses with expert judgment of asset sensitivity to climate risk and criticality to the transportation system in Washington State and by assessing transportation infrastructure exposure to climate risks associated with sea level rise and river flooding in the region as a whole.

Evidence for impacts of climate change on coastal habitat is based on:

- model-based studies of projected impacts of sea level rise on tidal habitat showing significant changes in the composition and extent of coastal wetland habitats in Washington and Oregon;
- observations of extent and location of coastal armoring and other structures that would potentially impede inland movement of coastal wetlands;
- observed changes in coastal ocean conditions (upwelling, nutrients, and sea surface temperatures); biogeographical, physiological, and paleoecological studies indicating a historical decline in coastal upwelling; and global climate model projections of future increases in sea surface temperatures;
- modeled projections for increased risk of harmful algal blooms (HABs) in Puget Sound associated with higher air and water temperatures, reduced streamflow, low winds, and small tidal variability (i.e., these conditions offer a favorable window of opportunity for HABs); and
- observed changes in the geographic ranges, migration timing, and productivity of marine species due to changes in sea surface temperatures associated with cyclical events, such as the interannual El Niño Southern Oscillation and the inter-decadal Pacific Decadal Oscillation and North Pacific Gyre Oscillation.

Evidence for historical increases in ocean acidification is from observations of changes in coastal ocean conditions, which also indicate high spatial and temporal variability. Evidence for acidification's effects on various species and the broader marine food web is still emerging but is based on observed changes in abundance, size, and mortality of marine calcifying organisms and laboratory based and in situ acidification experiments.

Evidence for marine species responses to climate change derives from observations of shifts in marine plankton, fish, and seabird species associated with historical changes in ocean conditions, including temperature and availability of preferred foods.

Evidence for low adaptive capacity is from observations of extent of degraded or fragmented coastal habitat, existence of few options for mitigating changes in marine chemical properties, observed extent of barriers to inland habitat migration, narrow coastal transportation corridors, and limited transportation alternatives for rural coastal towns. Evidence for low adaptive capacity is also based on the current limitations (both legal and political) of local and state governments to restrict and/or influence shoreline modifications on private lands.

New information and remaining uncertainties

There is significant but well-characterized uncertainty about the rate and extent of future sea level rise at both the global and regional/sub-regional scales. However, there is virtually no uncertainty in the direction (sign) of global sea level rise. There is also a solid understanding of the primary contributing factors and mechanisms causing sea level rise. Other details concerning uncertainty in global sea level rise are treated elsewhere (for example, NRC 2012[50]) and in Ch. 2: Our Changing Climate). Regional uncertainty in projected Northwest sea level rise results primarily from global factors such as ice sheet mass balance and local vertical land movement (affecting relative sea level rise). An accurate determination of vertical land deformation requires a sufficient density of monitoring sites (for example, NOAA tide gauges and permanent GPS sites that monitor deformation) to capture variations in land deformation over short spatial scales, and in many Northwest coastal locations such dense networks do not exist. There is a general trend, however, of observed uplift along the northwestern portion of the Olympic Peninsula and of subsidence within the Puget Sound region (GPS data gathered from PBO data sets -- http://pbo.unavco.org/data/gps; see also Chapman and Melbourne 2009[51]).

There is also considerable uncertainty about potential impacts of climate change on processes that influence storminess and affect coastal erosion in the Northwest. These uncertainties relate to system complexity and the limited number of studies and lack of consensus on future atmospheric and oceanic conditions that will drive changes in regional wind fields. Continued collection and assessment of meteorological data at ocean buoy locations and via remote sensing should improve our understanding of these processes.

Uncertainty in future patterns of sediment delivery to the coastal system limit projections of future inundation, erosion, and changes in tidal marsh. For example, substantial increases in riverine sediment delivery, due to climate-related changes in the amount and timing of streamflow, could offset erosion and/or inundation projected from changes in sea level alone. However, there are areas in the Northwest where it is clear that man-made structures have interrupted sediment supply and there is little uncertainty that shallow water habitat will be lost.

Although relatively well-bounded, uncertainty over the rate of projected relative sea level rise limits our ability to assess whether any particular coastal habitat will be able to keep pace with future changes through adaptation (for example, through accretion).

The specific implications of the combined factors of sea level rise, coastal climate change, and ocean acidification for coastal ecosystems and specific individual species remain uncertain due to the complexity of ecosystem response. However, there is general agreement throughout the peer-reviewed literature that negative impacts for a number of marine calcifying organisms are projected, particularly during juvenile life stages.

Projections of future coastal ocean conditions (for example, temperature, nutrients, pH, and productivity) are limited, in part, by uncertainty over future changes in upwelling – climate model scenarios show inconsistent projections for likely future upwelling conditions. Considerable uncertainty also remains in whether, and how, higher average ocean temperatures will influence geographical ranges, abundances, and diversity of marine species, although evidence of changes in pelagic fish species ranges and in production associated with Pacific Ocean temperature variability during cyclical events have been important indicators for potential species responses to climate change in the future. Consequences from ocean acidification for commercial fisheries and marine food web dynamics are potentially very high – while the trend of increasing acidification is very likely, the rate of change and spatial variability within coastal waters are largely unknown and are the subject of ongoing and numerous nascent research efforts.

Additional uncertainty surrounds non-climate contributors to coastal ocean chemistry (for example, riverine inputs, anthropogenic carbon, and nitrogen point and non-point source inputs) and society's ability to mitigate these inputs.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

There is **very high** confidence in the global upward trend of sea level rise (SLR) and ocean acidification (OA). There is **high** confidence that SLR over the next century will remain under an upper bound of approximately 2 meters. Projections for SLR and OA at specific locations are much less certain (**medium to low**) because of the high spatial variability and multiple factors influencing both phenomena at regional and sub-regional scales.

There is **medium** confidence in the projections of species response to sea level rise and increased temperatures, but **low** confidence in species response to ocean acidification. Uncertainty in upwelling changes result in **low** confidence for projections of future change that depend on specific coastal ocean temperatures, nutrient contents, dissolved oxygen content, stratification, and other factors.

There is **high** confidence that significant changes in the type and distribution of coastal marsh habitat are likely, but **low** confidence in our current ability to project the specific location and timing of changes.

There is **high** confidence in the projections of increased erosion and inundation.

There is **very high** confidence that ocean acidity will continue to increase.

KEY MESSAGE #3 TRACEABLE ACCOUNT

The combined impact of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.

Description of evidence base

Evidence that the area burned by fire has been high, relative to earlier in the century, since at least the 1980s is strong. Peer-reviewed papers based on federal fire databases (for example, National Interagency Fire Management Integrated Database [NIFMID], 1970/1980-2011) and independent satellite data (Monitoring Trends in Burn Severity [MTBS], 1984-2011) indicate increases in area burned.[98,126]

Evidence that the interannual variation in area burned was at least partially controlled by climate during the period 1980-2010 is also strong. Statistical analysis has shown that increased temperature (related to increased potential evapotranspiration, relative humidity, and longer fire seasons) and decreased precipitation (related to decreased actual evapotranspiration, decreased spring snowpack, and longer fire seasons) are moderate to strong (depending on forest type) correlates to the area and number of fires in the Pacific Northwest. Projections of area burned with climate change are documented in peer-reviewed literature, and different approaches (statistical modeling and dynamic global vegetation modeling) agree on the order of magnitude of those changes for Pacific Northwest forests, though the degree of increase depends on the climate change scenario and modeling approach.

Evidence from aerial disease and detection surveys jointly coordinated by the U.S. Forest Service and state level governments supports the statement that the area of forest mortality caused by insect outbreaks (including the mountain pine beetle) and by tree diseases is increasing.

Evidence that mountain pine beetle and spruce bark beetle outbreaks are climatically controlled is from a combination of laboratory experiments and mathematical modeling reported in peer-reviewed literature. Peer-reviewed future projections of climate have been used to develop projections of mountain pine beetle and spruce beetle habitat suitability based on these models, and show increases in the area of climatically suitable habitat (particularly at mid- to high elevations) by the mid-21st century, but subsequent (late 21st century) declines in suitable habitat, particularly at low- to mid-elevation. There is considerable spatial variability in the patterns of climatically suitable habitat.

Evidence for long-term changes in the distribution of vegetation types and tree species comes from statistical species models, dynamic vegetation models, and other approaches and uses the correlation between observed climate and observed vegetation distributions to model future climatic suitability. These models agree broadly in their conclusions that future climates will be unsuitable for historically present species over significant areas of their ranges and that broader vegetation types will likely change, but the details depend greatly on climate change scenario, location within the region, and forest type.

Evidence that subalpine forests are likely to undergo almost complete conversion to other vegetation types is moderately strong (relatively few studies, but good agreement) and comes from dynamic global vegetation models that include climate, statistical models that relate climate and biome distribution, and individual statistical species distribution models based on climatic variables. The fact that these three different approaches generally agree about the large decrease in area of subalpine forests despite different assumptions, degrees of "mechanistic" simulation, and levels of ecological hierarchy justifies the key message.

New information and remaining uncertainties

The key uncertainties are primarily the timing and magnitude of future projected changes in forests, rather than the direction (sign) of changes.

The rate of expected change is affected by the rate of climate change – higher emissions scenarios have higher impacts earlier in studies that consider multiple scenarios. Most impacts analyses reported in the literature and synthesized here use emissions scenario A1B or A2. Projections of changes in the proportion of Northwest pine forests where mountain pine beetles are likeliest to survive and of potential conversion of subalpine forests used scenario A2.

Statistical fire models do not include changes in vegetation that occur in the 21st century due to disturbance (such as fire, insects, and tree diseases) and other factors such as land-use change and fire suppression changes. As conditions depart from the period used for model training, projections of future fire become more uncertain, and by the latter 21st century (beyond about the 2060s to 2080s), statistical models may over-predict area burned. Despite this uncertainty, the projections from statistical models are broadly similar to those from dynamic global vegetation models (DGVMs), which explicitly simulate changes in future vegetation. A key difference is for forest ecosystems where fire has been rare since the mid 20th century, such as the Olympic Mountains and Oregon coast range, and statistical models are comparatively weak. In these systems, statistical fire models likely underestimate the future area burned, whereas DGVMs may capably simulate future events that are outside the range of the statistical model's capability. In any case, an increase in forest area burned is nearly ubiquitous in these studies regardless of method, but the amount of increase and the degree to which it varies with forest type is less certain. However, fire risk in any particular location or at any particular time is beyond the capability of current model projections. In addition, the statistical model approaches to future fire cannot address fundamental changes in fire behavior due to novel extreme weather patterns, so conclusions about changes in fire severity are not necessarily warranted.

Only a few insects have had sufficient study to understand their climatic linkages, and future insect outbreak damage from other insects, currently unstudied, could increase the estimate of future areas of forest mortality due to insects.

Fire-insect interactions and diseases are poorly studied – the actual effects on future landscapes could be greater if diseases and interactions were considered more explicitly.

For subalpine forests, what those forests become instead of subalpine forests is highly uncertain – different climate models used to drive the same dynamic global vegetation model agree about loss of subalpine forests, but disagree about what will replace them. In addition, statistical approaches that consider biome level and species level responses without the ecological process detail of DGVMs show similar losses, but do not agree on responses, which depend on climate scenarios. Because these statistical models simulate neither the regeneration of seedlings nor the role of disturbances, the future state of the system is merely correlative and based on the statistical relationship between climate and historical forest distribution.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

The observed effects of climate on fires and insects combined with the agreement of future projections across modeling efforts warrants **very high** confidence that increased disturbance will increase forest mortality due to area burned by fire, and increases in insect outbreaks also have **very high** confidence until at least the 2040s in the Northwest. The timing and nature of the rates and the sources of mortality may change, but current estimates may be conservative for insect outbreaks due to the unstudied impacts of other insects. But in any case, the rate of projected forest disturbance suggests that changes will be driven by disturbance more than by gradual changes in forest cover or species composition. After mid-21st century, uncertainty about the interactions between disturbances and landscape response limits confidence to **high** because total area disturbed could begin to decline as most of the landscape becomes outside the range of historical conditions. The fact that different modeling approaches using a wide variety of climate scenarios indicate similar losses of subalpine forests justifies **high** confidence; however, comparatively little research that simulates ecological processes of both disturbance and regeneration as a function of climate, so there is **low** confidence on what will replace them.

KEY MESSAGE #4 TRACEABLE ACCOUNT

While agriculture's technical ability to adapt to changing conditions can offset some of the adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.

Description of evidence base

Northwest agriculture's sensitivity to climate change stems from its dependence on irrigation water, adequate temperatures, precipitation and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming trends based on global climate models and emissions scenarios potentially increase temperature-related stress on annual and perennial crops in the summer months.

Evidence for projected impacts of warming on crop yields consists primarily of published studies using crop models indicating increasing vulnerability with projected warming over 1975-2005 baselines. These models also project that thermal-stress-related losses in agricultural productivity will be offset or overcompensated by fertilization from accompanying increases in atmospheric CO_2. These models have been developed for key commodities including wheat, apples, and potatoes. Longer term, to end of century, models project crop losses from temperature stress to exceed the benefits of CO_2 fertilization.

Evidence for the effects of warming on suitability of parts of the region for specific wine grape and tree fruit varieties are based on well-established and published climatic requirements for these varieties.

Evidence for negative impacts of increased variability of precipitation on livestock productivity due to stress on range and pasture consists of a few economic studies in states near the region; relevance to Northwest needs to be established.

Evidence for negative impacts of warming on dairy production in the region is based on a published study examining projected summer heat-stress on milk production.

Evidence for reduction in available irrigation water is based on peer-reviewed publications and state and federal agency reports utilizing hydrological models and precipitation and snowpack projections. These are outlined in more detail in the traceable account for Key Message 1 of this chapter. Increased demands for irrigation water with warming are based on cropping systems models and projected increases in acres cultivated. These projections, coupled with those for water supply, indicate that some areas will experience increased water shortages. Water rights records allow predictions of the users most vulnerable to the effects of these shortages.

Projections for surface water flows include decreases in summer flow related to changes in snowpack dynamics and reductions in summer precipitation. Although these precipitation projections are less certain than those concerning temperatures, they indicate that water shortages for irrigation will be more frequent in some parts of the region, based especially on a Washington State Department of Ecology-sponsored report that considered the Columbia basin. Other evidence for these projected changes in water is itemized in Key Message 1 of this chapter.

Evidence that agriculture has a high potential for autonomous adaptation to climate change, assuming adequate water availability, is inferred primarily from the wide range of production practices currently being used across the varied climates of the region.

New information and remaining uncertainties

Although increasing temperatures can affect the distribution of certain pest, weed, and pathogen species, existing models are limited. Without more comprehensive studies, it is not possible to project changes in overall pressure from these organisms, so overall effects remain uncertain. Some species may be adversely affected by warming directly or through enhancement of their natural enemy base, while others become more serious threats.

Uncertainty exists in models in how increasing temperatures will impact crop evapotranspiration, which affects future estimates of irrigation demand (Key Message 1 of this chapter).

Shifting international market forces including commodity prices and input costs, adoption of new crops, which may have different heat tolerance or water requirements, and technological advances are difficult or impossible to project, but may have substantial effects on agriculture's capacity to adapt to climate change.

Estimates of changes in crop yields as a result of changing climate and CO_2 are based on very few model simulations, so the uncertainty has not been well quantified.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

Confidence is **very high** based on strong strength of evidence and high level of agreement among experts.

See specifics under "description of evidence" above.

Climate Change Impacts in the United States

CHAPTER 22
ALASKA

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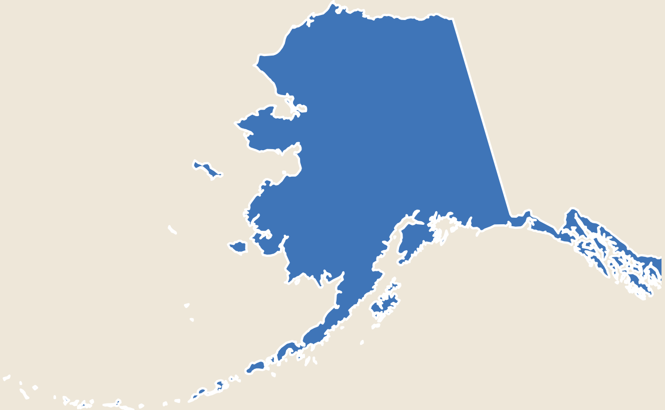

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

22 ALASKA

Key Messages

1. **Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.**
2. **Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.**
3. **Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.**
4. **Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.**
5. **The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.**

Alaska is the United States' only Arctic region. Its marine, tundra, boreal (northern) forest, and rainforest ecosystems differ from most of those in other states and are relatively intact. Alaska is home to millions of migratory birds, hundreds of thousands of caribou, some of the world's largest salmon runs, a significant proportion of the nation's marine mammals, and half of the nation's fish catch.[1]

Energy production is the main driver of the state's economy, providing more than 80% of state government revenue and thousands of jobs.[2] Continuing pressure for oil, gas, and mineral development on land and offshore in ice-covered waters increases the demand for infrastructure, placing additional stresses on ecosystems. Land-based energy exploration will be affected by a shorter season when ice roads are viable, yet reduced sea ice extent may create more opportunity for offshore development. Climate also affects hydropower generation.[3] Mining and fishing are the second and third largest industries in the state, with tourism rapidly increasing since the 1990s.[2] Fisheries are vulnerable to changes in fish abundance and dis-


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tribution that result from both climate change and fishing pressure. Tourism might respond positively to warmer springs and autumns[4] but negatively to less favorable conditions for winter activities and increased summer smoke from wildfire.[5]

Alaska is home to 40% (229 of 566) of the federally recognized tribes in the United States.[6] The small number of jobs, high cost of living, and rapid social change make rural, predominantly Native, communities highly vulnerable to climate change through impacts on traditional hunting and fishing and cultural connection to the land and sea. Because most of these communities are not connected to the state's road system or electrical grid, the cost of living is high, and it is challenging to supply food, fuel, materials, health care, and other services. Climate impacts on these communities are magnified by additional social and economic stresses. However, Alaskan Native communities have for centuries dealt with scarcity and high environmental variability and thus have deep cultural reservoirs of flexibility and adaptability.

Observed Climate Change

Over the past 60 years, Alaska has warmed more than twice as rapidly as the rest of the United States, with state-wide average annual air temperature increasing by 3°F and average winter temperature by 6°F, with substantial year-to-year and regional variability.[7] Most of the warming occurred around 1976 during a shift in a long-lived climate pattern (the Pacific Decadal Oscillation [PDO]) from a cooler pattern to a warmer one. The PDO has been shown to alternate over time between warm and cool phases. The underlying long-term warming trend has moderated the effects of the more recent shift of the PDO to its cooler phase in the early 2000s.[8] The overall warming has involved more extremely hot days and fewer extremely cold days (Ch. 2: Our Changing Climate, Key Message 7).[7,9]

Because of its cold-adapted features and rapid warming, climate change impacts on Alaska are already pronounced, including earlier spring snowmelt, reduced sea ice, widespread glacier retreat, warmer permafrost, drier landscapes, and more extensive insect outbreaks and wildfire, as described below.

Projected Climate Change

Average annual temperatures in Alaska are projected to rise by an additional 2°F to 4°F by 2050. If global emissions continue to increase during this century, temperatures can be expected to rise 10°F to 12°F in the north, 8°F to 10°F in the interior, and 6°F to 8°F in the rest of the state. Even with substantial emissions reductions, Alaska is projected to warm by 6°F to 8°F in the north and 4°F to 6°F in the rest of the state by the end of the century (Ch. 2: Our Changing Climate, Key Message 3).[7,10]

Annual precipitation is projected to increase, especially in northwestern Alaska,[7] as part of the broad pattern of increases projected for high northern latitudes. Annual precipitation increases of about 15% to 30% are projected for the region by late this century if global emissions continue to increase (A2). All models project increases in all four seasons.[7] However, increases in evaporation due to higher air temperatures and longer growing seasons are expected to reduce water availability in most of the state.[11]

The length of the growing season in interior Alaska has increased 45% over the last century[12] and that trend is projected to continue.[13] This could improve conditions for agriculture where moisture is adequate, but will reduce water storage and increase the risks of more extensive wildfire and insect outbreaks across much of Alaska.[14,15]

Alaska Will Continue to Warm Rapidly

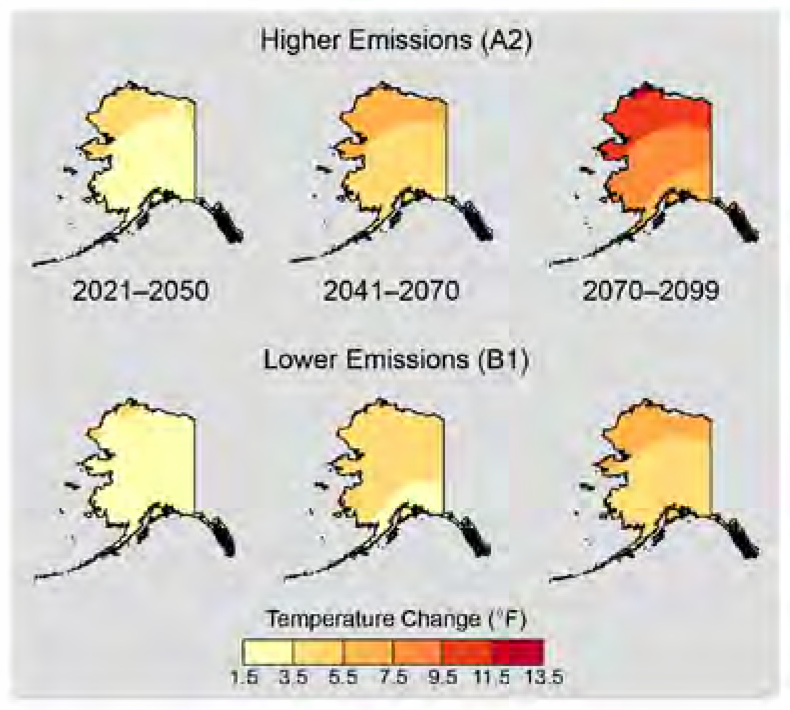

Figure 22.1. Northern latitudes are warming faster than more temperate regions, and Alaska has already warmed much faster than the rest of the country. Maps show changes in temperature, relative to 1971-1999, projected for Alaska in the early, middle, and late parts of this century, if heat-trapping gas (also known as greenhouse gas) emissions continue to increase (higher emissions, A2), or are substantially reduced (lower emissions, B1). (Figure source: adapted from Stewart et al. 2013[7]).

Changes in dates of snowmelt and freeze-up would influence seasonal migration of birds and other animals, increase the likelihood and rate of northerly range expansion of native and non-native species, alter the habitats of both ecologically important and endangered species, and affect ocean currents.[16]

Key Message 1: Disappearing Sea Ice

Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.

Arctic sea ice extent and thickness have declined substantially, especially in late summer (September), when there is now only about half as much sea ice as at the beginning of the satellite record in 1979 (Ch. 2: Our Changing Climate, Key Message 11).[17,18] The seven Septembers with the lowest ice extent all occurred in the past seven years. As sea ice declines, it becomes thinner, with less ice build-up over multiple years, and therefore more vulnerable to further melting.[18] Models that best match historical trends project northern waters that are virtually ice-free by late summer by the 2030s.[19,20] Within the general downward trend in sea ice, there will be time periods with both rapid ice loss and temporary recovery,[21] making it challenging to predict short-term changes in ice conditions.

Declining Sea Ice Extent

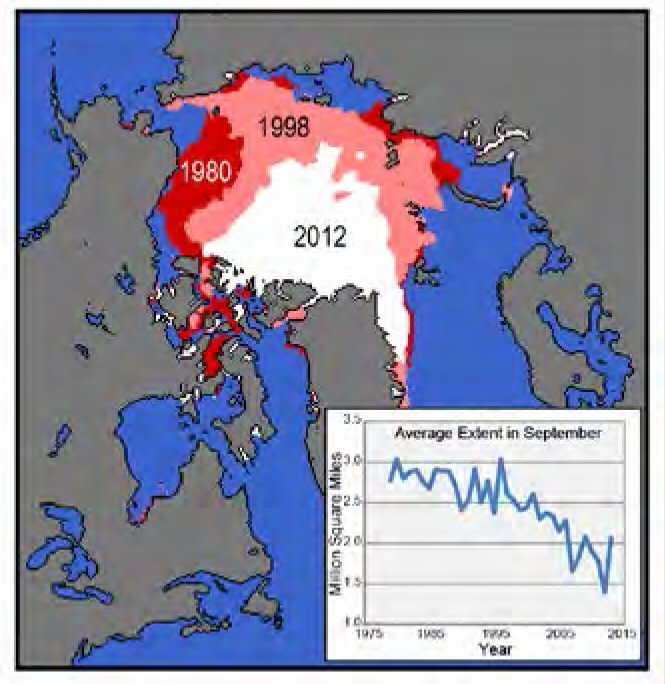

Figure 22.2. Average September extent of Arctic sea ice in 1980 (second year of satellite record and year of greatest September sea ice extent; outer red boundary), 1998 (about halfway through the time series; outer pink boundary) and 2012 (recent year of record and year of least September sea ice extent; outer white boundary). September is typically the month when sea ice is least extensive. Inset is the complete time series of average September sea ice extent (1979-2013). (Figure source: NSIDC 2012; Data from Fetterer et al. 2013[22]).

Reductions in sea ice increase the amount of the sun's energy that is absorbed by the ocean. This leads to a self-reinforcing climate cycle, because the warmer ocean melts more ice, leaving more dark open water that gains even more heat. In autumn and winter, there is a strong release of this extra ocean heat back to the atmosphere. This is a key driver of the observed increases in air temperature in the Arctic.[23] This strong warming linked to ice loss can influence atmospheric circulation and patterns of precipitation, both within and beyond the Arctic (for example, Porter et al. 2012[24]). There is growing evidence that this has already occurred[25] through more evaporation from the ocean, which increases water vapor in the lower atmosphere[26] and autumn cloud cover west and north of Alaska.[27]

With reduced ice extent, the Arctic Ocean is more accessible for marine traffic, including trans-Arctic shipping, oil and gas

Sea Ice Loss Brings Big Changes to Arctic Life

Figure 22. 3. Reductions in sea ice alter food availability for many species from polar bear to walrus, make hunting less safe for Alaska Native hunters, and create more accessibility for Arctic Ocean marine transport, requiring more Coast Guard coverage. (Photo credits: (top left) G. Carleton Ray; (bottom left) Daniel Glick; (right) Patrick Kelley).

exploration, and tourism.[28] This facilitates access to the substantial deposits of oil and natural gas under the seafloor in the Beaufort and Chukchi seas, as well as raising the risk to people and ecosystems from oil spills and other drilling and maritime-related accidents. A seasonally ice-free Arctic Ocean also increases sovereignty and security concerns as a result of potential new international disputes and increased possibilities for marine traffic between the Pacific and Atlantic Oceans.[10]

Polar bears are one of the most sensitive Arctic marine mammals to climate warming because they spend most of their lives on sea ice.[29] Declining sea ice in northern Alaska is associated with smaller bears, probably because of less successful hunting of seals, which are themselves ice-dependent and so are projected to decline with diminishing ice and snow cover.[30] Although bears can give birth to cubs on sea ice, increasing numbers of female bears now come ashore in Alaska in the summer and fall[31] and den on land.[32] In Hudson Bay, Canada, the most studied population in the Arctic, sea ice is now absent for three weeks longer than just a few decades ago, resulting in less body fat, reduced survival of both the youngest and oldest bears,[33] and a population now estimated to be in decline[34] and projected to be in jeopardy.[35] Similar polar bear population declines are projected for the Beaufort Sea region.[36]

Walrus depend on sea ice as a platform for giving birth, nursing, and resting between dives to the seafloor, where they feed.[37] In recent years, when summer sea ice in the Chukchi Sea retreated over waters that were too deep for walrus to feed,[38] large numbers of walrus abandoned the ice and came ashore. The high concentration of animals results in increased competition for food and can lead to stampedes when animals are startled, resulting in trampling of calves.[39] This movement to land first occurred in 2007 and has happened three times since then, suggesting a threshold change in walrus ecology.

LIVING ON THE FRONT LINES OF CLIMATE CHANGE

"Not that long ago the water was far from our village and could not be easily seen from our homes. Today the weather is changing and is slowly taking away our village. Our boardwalks are warped, some of our buildings tilt, the land is sinking and falling away, and the water is close to our homes. The infrastructure that supports our village is compromised and affecting the health and well-being of our community members, especially our children."

– Alaska Department of Commerce and Community and Economic Development, 2012[44]

Newtok, a Yup'ik Eskimo community on the seacoast of western Alaska, is on the front lines of climate change. Between October 2004 and May 2006, three storms accelerated the erosion and repeatedly "flooded the village water supply, caused raw sewage to be spread throughout the community, displaced residents from homes, destroyed subsistence food storage, and shut down essential utilities."[45] The village landfill, barge ramp, sewage treatment facility, and fuel storage facilities were destroyed or severely damaged.[46] The loss of the barge landing, which delivered most supplies and heating fuel, created a fuel crisis. Saltwater is intruding into the community water supply. Erosion is projected to reach the school, the largest building in the community, by 2017.

Recognizing the increasing danger from coastal erosion, Newtok has worked for a generation to relocate to a safer location. However, current federal legislation does not authorize federal or state agencies to assist communities in relocating, nor does it authorize them to repair or upgrade storm-damaged infrastructure in flood-prone locations like Newtok.[42] Newtok therefore cannot safely remain in its current location nor can it access public funds to adapt to climate change through relocation.

Newtok's situation is not unique. At least two other Alaskan communities, Shishmaref and Kivalina, also face immediate threat from coastal erosion and are seeking to relocate, but have been unsuccessful in doing so. Many of the world's largest cities are coastal and are also exposed to climate change induced flood risks.[47]

Newtok, Alaska

Figure 22.4. Residents in Newtok, Alaska are living with the effects of climate change, with thawing permafrost, tilting houses, sinking boardwalks, in conjunction with aging fuel tanks and other infrastructure that cannot be replaced because of laws that prevent public investment in flood-prone localities. (Photo credit: F. S. Chapin III).

With the late-summer ice edge located farther north than it used to be, storms produce larger waves and more coastal erosion.[10] An additional contributing factor is that coastal bluffs that were “cemented” by ice-rich permafrost are beginning to thaw in response to warmer air and ocean waters, and are therefore more vulnerable to erosion.[40] Standard defensive adaptation strategies to protect coastal communities from erosion, such as use of rock walls, sandbags, and riprap, have been largely unsuccessful.[41] Several coastal communities are seeking to relocate to escape erosion that threatens infrastructure and services but, because of high costs and policy constraints on use of federal funds for community relocation, only one Alaskan village has begun to relocate (see also Ch. 12: Indigenous Peoples).[42,43]

Key Message 2: Shrinking Glaciers

Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.

Alaska is home to some of the largest glaciers and fastest loss of glacier ice on Earth.[48,49,50] This rapid ice loss is primarily a result of rising temperatures (for example, Arendt et al. 2002, 2009[51,52,53]; Ch. 2: Our Changing Climate, Key Message 11). Loss of glacial volume in Alaska and neighboring British Columbia, Canada, currently contributes 20% to 30% as much surplus freshwater to the oceans as does the Greenland Ice Sheet – about 40 to 70 gigatons per year,[49,54,55,56] comparable to 10% of the annual discharge of the Mississippi River.[57] Glaciers continue to respond to climate warming for years to decades after warming ceases, so ice loss is expected to continue, even if air temperatures were to remain at current levels. The global decline in glacial and ice-sheet volume is predicted to be one of the largest contributors to global sea level rise during this century (Ch. 2: Our Changing Climate, Key Message 10).[58,59]

Water from glacial landscapes is also recognized as an important source of organic carbon,[60,61] phosphorus,[62] and iron[63] that contribute to high coastal productivity, so changes in these inputs could alter critical nearshore fisheries.[61,64]

Glaciers supply about half of the total freshwater input to the Gulf of Alaska.[65] Glacier retreat currently increases river discharge and hydropower potential in south central and southeast Alaska, but over the longer term might reduce water input to reservoirs and therefore hydropower resources.[3]

On the left is a photograph of Muir Glacier in Alaska taken on August 13, 1941; on the right, a photograph taken from the same vantage point on August 31, 2004. Total glacial mass has declined sharply around the globe, adding to sea level rise. (Left photo by glaciologist William O. Field; right photo by geologist Bruce F. Molnia of the United States Geological Survey.)

Key Message 3: Thawing Permafrost

Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.

Alaska differs from most of the rest of the U.S. in having permafrost – frozen ground that restricts water drainage and therefore strongly influences landscape water balance and the design and maintenance of infrastructure. Permafrost near the Alaskan Arctic coast has warmed 4°F to 5°F at 65 foot depth[66,67] since the late 1970s and 6°F to 8°F at 3.3 foot depth since the mid-1980s.[68] In Alaska, 80% of land is underlain by permafrost, and of this, more than 70% is vulnerable to subsidence upon thawing because of ice content that is either variable, moderate, or high.[69] Thaw is already occurring in interior and southern Alaska and in northern Canada, where permafrost temperatures are near the thaw point.[70] Models project that permafrost in Alaska will continue to thaw,[71,72] and some models project that near-surface permafrost will be lost entirely from large parts of Alaska by the end of the century.[73]

Uneven sinking of the ground in response to permafrost thaw is estimated to add between $3.6 and $6.1 billion (10% to 20%) to current costs of maintaining public infrastructure such as buildings, pipelines, roads, and airports over the next 20 years.[74] In rural Alaska, permafrost thaw will likely disrupt community water supplies and sewage systems,[75,76,77] with negative effects on human health.[78] The period during which oil and gas exploration is allowed on tundra has decreased by 50% since the 1970s as a result of permafrost vulnerability.[11]

On average, lakes have decreased in area in the last 50 years in the southern two-thirds of Alaska,[80,81,82] due to a combination of permafrost thaw, greater evaporation in a warmer climate, and increased soil organic accumulation during a longer season for plant growth. In some places, however, lakes are getting larger because of lateral permafrost degradation.[81] Future permafrost thaw will likely increase lake area in areas of continuous permafrost and decrease lake area in places where the permafrost zone is more fragmented.[71]

A continuation of the current drying of Alaskan lakes and wetlands could affect waterfowl management nationally because Alaska accounts for 81% of the National Wildlife Refuge System and provides breeding habitat for millions of migratory birds that winter in more southerly regions of North America and on other continents.[83] Wetland loss would also reduce waterfowl harvest in Alaska, where it is an important food source for Alaska Natives and other rural residents.

The Big Thaw

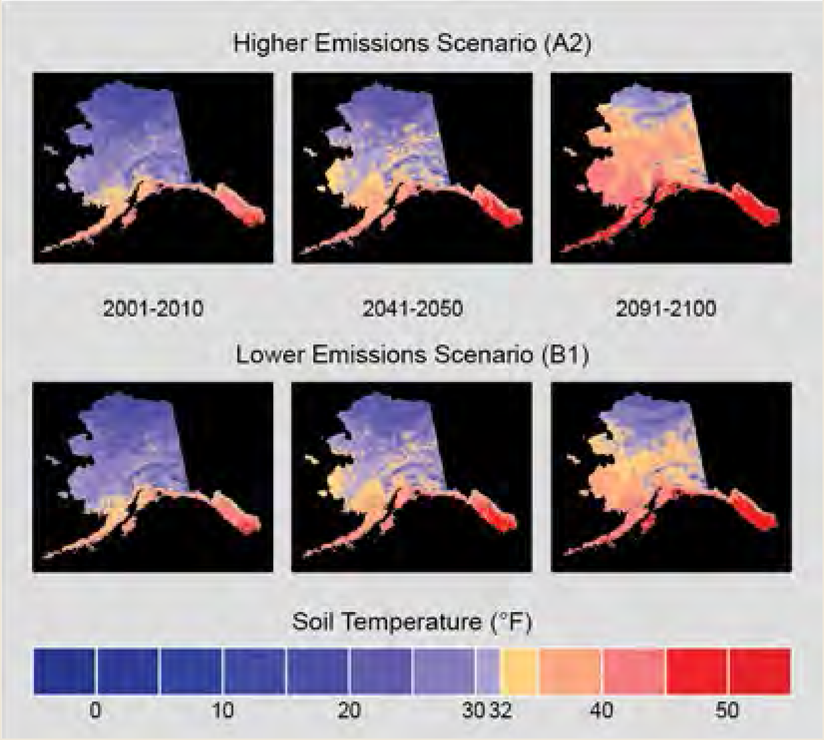

Figure 22.5. Projections for average annual ground temperature at a depth of 3.3 feet over time if emissions of heat-trapping gases continue to grow (higher emissions scenario, A2), and if they are substantially reduced (lower emissions scenario, B1). Blue shades represent areas below freezing at a depth of 3.3 feet, and yellow and red shades represent areas above freezing at that depth, based on the GIPL 1.0 model. (Figure source: Permafrost Lab, Geophysical Institute, University of Alaska Fairbanks).

Both wetland drying and the increased frequency of warm dry summers and associated thunderstorms have led to more large fires in the last ten years than in any decade since record-keeping began in the 1940s.[14] In Alaskan tundra, which was too cold and wet to support extensive fires for approximately the last 5,000 years,[84] a single large fire in 2007 released as much carbon to the atmosphere as had been absorbed by the entire circumpolar Arctic tundra during the previous quarter-century.[85] Even if climate warming were curtailed by reducing heat-trapping gas (also known as greenhouse gas) emissions (as in the B1 scenario), the annual area burned in Alaska is projected to double by mid-century and to triple by the end of the century,[86] thus fostering increased emissions of heat-trapping gases, higher temperatures, and increased fires. In addition, thick smoke produced in years of extensive wildfire represents a human health risk (Ch. 9: Human Health). More extensive and severe wildfires could shift the forests of Interior Alaska during this century from dominance by spruce to broadleaf trees for the first time in the past 4,000 to 6,000 years.[87,88]

Wildfire has mixed effects on habitat. It generally improves habitat for berries, mushrooms, and moose,[58,89] but reduces winter habitat for caribou because lichens, a key winter food source for caribou, require 50 to 100 years to recover after wildfire.[90] These habitat changes are nutritionally and culturally significant for Alaska Native Peoples.[89,91] In addition, exotic plant species that were introduced along roadways are now spreading onto river floodplains and recently burned forests,[92] potentially changing the suitability of these lands for timber production and wildlife. Some invasive species are toxic to moose, on which local people depend for food.[93]

Mounting Expenses from Permafrost Thawing

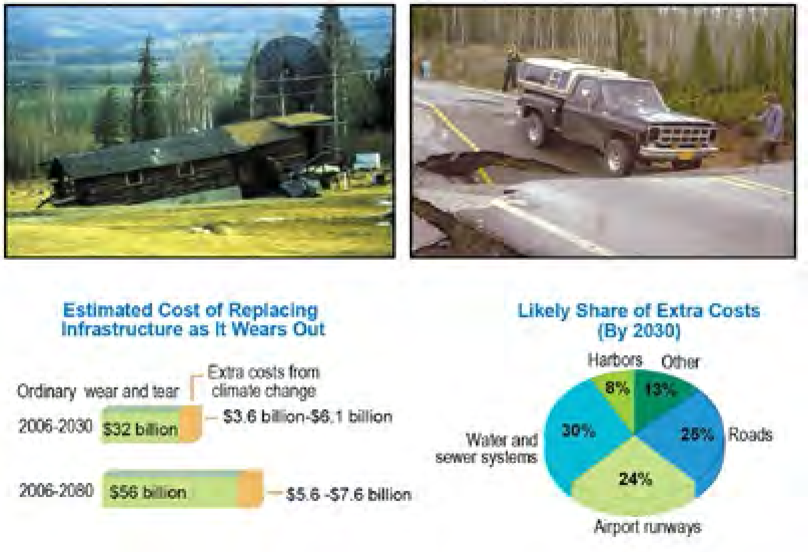

Figure 22.6. Effects of permafrost thaw on houses in interior Alaska (2001, top left), roads in eastern Alaska (1982, top right), and the estimated costs (with and without climate change) of replacing public infrastructure in Alaska, assuming a mid-range emissions scenario (A1B, with some decrease from current emissions growth trends). (Photo credits: (top left) Larry Hinzman; (top right) Joe Moore. Figure source: adapted from Larsen and Goldsmith 2007[79]).

Drying Lakes and Changing Habitat

Figure 22.7. Progressive drying of lakes in northern forest wetlands in the Yukon Flats National Wildlife Refuge, Alaska. Foreground orange area was once a lake. Mid-ground lake once extended to the shrubs. (Photo credit: May-Le Ng).

Changes in terrestrial ecosystems in Alaska and the Arctic may be influencing the global climate system. Permafrost soils throughout the entire Arctic contain almost twice as much carbon as the atmosphere.[94] Warming and thawing of these soils increases the release of carbon dioxide and methane through increased decomposition. Thawing permafrost also delivers organic-rich soils to lake bottoms, where decomposition in the absence of oxygen releases additional methane.[95] Extensive wildfires also release carbon that contributes to climate warming.[86,96] The capacity of the Yukon River Basin in Alaska and adjacent Canada to store carbon has been substantially weakened since the 1960s by the combination of warming and thawing of permafrost and by increased wildfire.[97] Expansion of tall shrubs and trees into tundra makes the surface darker and rougher, increasing absorption of the sun's energy and further contributing to warming.[98] This warming is likely stronger than the potential cooling effects of increased carbon dioxide uptake associated with tree and shrub expansion.[99] The shorter snow-covered seasons in Alaska further increase energy absorption by the land surface, an effect only slightly offset by the reduced energy absorption of highly reflective post-fire snow-covered landscapes.[99] This spectrum of changes in Alaskan and other high-latitude terrestrial ecosystems jeopardizes efforts by society to use ecosystem carbon management to offset fossil fuel emissions.[94,100]

Key Message 4: Changing Ocean Temperatures and Chemistry

Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.

Ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes interact to affect the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence.[101,102,103] These changes have allowed some near-surface fish species such as salmon to expand their ranges northward along the Alaskan coast.[104] In addition, non-native species are invading Alaskan waters more rapidly, primarily through ships releasing ballast waters and bringing southerly species to Alaska.[10,105] These species introductions could affect marine ecosystems, including the feeding relationships of fish important to commercial and subsistence fisheries.

Overall habitat extent is expected to change as well, though the degree of the range migration will depend upon the life history of particular species. For example, reductions in seasonal sea ice cover and higher surface temperatures may open up new habitat in polar regions for some important fish species, such as cod, herring, and pollock.[106] However, continued presence of cold bottom-water temperatures on the Alaskan continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea off northwestern Alaska.[107] In addition, warming may cause reductions in the abundance of some species, such as pollock, in their current ranges in the Bering Sea[108] and reduce the health of juvenile sockeye salmon, potentially resulting in decreased overwinter survival.[109] If ocean warming continues, it is unlikely that current fishing pressure on pollock can be sustained.[110] Higher temperatures are also likely to increase the frequency of early Chinook salmon migrations, making management of the fishery by multiple user groups more challenging.[111]

The changing temperature and chemistry of the Arctic Ocean and Bering Sea are likely changing their role in global ocean circulation and as carbon sinks for atmospheric CO_2 respectively, although the importance of these changes in the global carbon budget remains unresolved. The North Pacific Ocean is particularly susceptible to ocean acidification (see also Ch. 2: Our Changing Climate, Key Message 12; Ch. 24: Oceans).[112] Acidifying changes in ocean chemistry have potentially widespread impacts on the marine food web, including commercially important species.

OCEAN ACIDIFICATION IN ALASKA

Ocean waters globally have become 30% more acidic due to absorption of large amounts of human-produced carbon dioxide (CO_2) from the atmosphere. This CO_2 interacts with ocean water to form carbonic acid that lowers the ocean's pH (ocean acidification). The polar ocean is particularly prone to acidification because of low temperature[113,114] and low salt content, the latter resulting from the large freshwater input from melting sea ice[115] and large rivers. Acidity reduces the capacity of key plankton species and shelled animals to form and maintain shells and other hard parts, and therefore alters the food available to important fish species.[113,116] The rising acidity will have particularly strong societal effects on the Bering Sea on Alaska's west coast because of its high-productivity commercial and subsistence fisheries.[102,117]

Shelled pteropods, which are tiny planktonic snails near the base of the food chain, respond quickly to acidifying conditions and are an especially critical link in high-latitude food webs, as commercially important species such as pink salmon depend heavily on them for food.[118] A 10% decrease in the population of pteropods could mean a 20% decrease in an adult pink salmon's body weight.[119] Pteropod consumption by juvenile pink salmon in the northern Gulf of Alaska varied 45% between 1999 and 2001, although the reason for this variation is unknown.[120]

At some times of year, acidification has already reached a critical threshold for organisms living on Alaska's continental shelves.[121] Certain algae and animals that form shells (such as clams, oysters, and crab) use carbonate minerals (aragonite and calcite) that dissolve below that threshold. These organisms form a crucial component of the marine food web that sustains life in the rich waters off Alaska's coasts. In addition, Alaska oyster farmers are now indirectly affected by ocean acidification impacts farther south because they rely on oyster spat (attached oyster larvae) from Puget Sound farmers who are now directly affected by the recent upwelling of acidic waters along the Washington and Oregon coastline (Ch. 24: Oceans; Ch. 21: Northwest).[122]

Key Message 5: Native Communities

The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

With the exception of oil-producing regions in the north, rural Alaska is one of the most extensive areas of poverty in the U.S. in terms of household income, yet residents pay the highest prices for food and fuel.[123] Alaska Native Peoples, who are the most numerous residents of this region, depend economically, nutritionally, and culturally on hunting and fishing for their livelihoods.[124,125,126] Hunters speak of thinning sea and river ice that makes harvest of wild foods more dangerous,[127] changes to permafrost that alter spring run-off patterns, a northward shift in seal and fish species, and rising sea levels with more extreme tidal fluctuations (see Ch. 12: Indigenous Peoples).[128,129] Responses to these changes are often constrained by regulations.[77,129] Coastal erosion is destroying infrastructure. Impacts of climate change on river ice dynamics and spring flooding are threats to river communities but are complex, and trends have not yet been well documented.[130]

Major food sources are under stress due to many factors, including lack of sea ice for marine mammals.[131] Thawing of near-surface permafrost beneath lakes and ponds that provide drinking water cause food and water security challenges for villages. Sanitation and health problems also result from deteriorating water and sewage systems, and ice cellars traditionally used for storing food are thawing (see also Ch. 12: Indigenous Peoples).[75,78] Warming also releases human-caused pollutants, such as poleward-transported mercury and organic pesticides, from thawing permafrost and brings new diseases to Arctic plants and animals, including subsistence food species, posing new health challenges, especially to rural communities.[132] Positive health effects of warming include a longer growing season for gardening and agriculture.[10,133]

Development activities in the Arctic (for example, oil and gas, minerals, tourism, and shipping) are of concern to Indigenous communities, from both perceived threats and anticipated benefits.[126] Greater levels of industrial activity might alter the distribution of species, disrupt subsistence activities, increase the risk of oil spills, and create various social impacts. At the same time, development provides economic opportunities, if it can be harnessed appropriately.[134]

Alaska Native Elders say, “We must prepare to adapt.” However, the implications of this simple instruction are multi-faceted. Adapting means more than adjusting hunting technologies and foods eaten. It requires learning how to garner information from a rapidly changing environment. Permanent infrastructure and specified property rights increasingly constrain people’s ability to safely use their environment for subsistence and other activities.

Traditional knowledge now facilitates adaptation to climate change as a framework for linking new local observations with western science.[124,135] The capacity of Alaska Natives to survive for centuries in the harshest of conditions reflects their resilience.[91] Communities must rely not only on improved knowledge of changes that are occurring, but also on support from traditional and other institutions – and on strength from within – in order to face an uncertain future.[124]

Alaska Coastal Communities Damaged

Figure 22.8: One effect of the reduction in Alaska sea ice is that storm surges that used to be buffered by the ice are now causing more shoreline damage. Photos show infrastructure damage from coastal erosion in Tuntutuliak (left) and Shishmaref, Alaska (right). (Photo credits: (left) Alaska Department of Environmental Conservation; (right) Ned Rozell).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for developing key messages

A central component of the assessment process was the Alaska Regional Climate assessment workshop that was held September 12-15, 2012, in Anchorage with approximately 20 attendees; it began the process leading to a foundational Technical Input Report (TIR).[10] The report consists of 148 pages of text, 45 figures, 8 tables, and 27 pages of references. Public and private citizens or institutions were consulted and engaged in its preparation and expert review by the various agencies and non-governmental organizations (NGOs) represented by the 11-member TIR writing team. The key findings of the report were presented at the Alaska Forum on the Environment and in a regularly scheduled, monthly webinar by the Alaska Center for Climate Assessment and Policy, with feedback then incorporated into the report.

The chapter author team engaged in multiple technical discussions via regular teleconferences. These included careful expert review of the foundational TIR[10] and of approximately 85 additional technical inputs provided by the public, as well as the other published literature and professional judgment. These discussions were followed by expert deliberation of draft key messages by the writing team in a face-to-face meeting before each key message was selected for inclusion in the Report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities" (Ch. 26: Decision Support).

KEY MESSAGE #1 TRACEABLE ACCOUNT

Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska TIR.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Although various models differ in the projected rate of sea ice loss, more recent CMIP5 models[20] that most accurately reconstruct historical sea ice loss project that late-summer sea ice will virtually disappear by the 2030s, leaving only remnant sea ice.

Evidence is strong about the impacts of sea ice loss.[10] Because the sea ice cover plays such a strong role in human activities and Arctic ecosystems, loss of the ice cover is nearly certain to have substantial impacts.[17]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

Evidence from improved models (for example, Wang and Overland 2012[20]) and updated observational data from satellite, especially new results, clearly show rapid decline in not only extent but also mass and thickness of multi-year ice,[18] information that was not available in prior assessments.

Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining and that, if heat-trapping gas concentrations continue to rise, an essentially ice-free summer Arctic ocean will be realized before mid-century. However, there remains uncertainty in the rate of sea ice loss, with the models that most accurately project historical sea ice trends currently suggesting nearly ice-free conditions sometime between 2021 and 2043 (median 2035).[20] Uncertainty across all models stems from a combination of large differences in projections among different climate models, natural climate variability, and uncertainty about future rates of fossil fuel emissions.

Ecosystems: There is substantial new information that ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes are affecting the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence.[101,102] However, the relative importance of these potential causes of change is highly uncertain.

Offshore oil and gas development: A key uncertainty is the price of fossil fuels. Viable avenues for improving the information base include determining the primary causes of variation among different climate models and determining which climate models exhibit the best ability to reproduce the observed rate of sea ice loss.

Coastal erosion: There is new information that lack of sea ice causes storms to produce larger waves and more coastal erosion.[10] An additional contributing factor is that coastal bluffs that were “cemented” by permafrost are beginning to thaw in response to warmer air and ocean waters, and are therefore more vulnerable to erosion.[40] Standard defensive adaptation strategies to protect coastal communities from erosion such as use of rock walls, sandbags, and riprap have been largely unsuccessful.[41] There remains considerable uncertainty, however, about the spatial patterns of future coastal erosion.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

Very high confidence for summer sea ice decline. **High** confidence for summer sea ice disappearing by mid-century.

Very high confidence for altered marine ecosystems, greater ship access, and increased vulnerability of communities to coastal erosion.

High confidence regarding offshore development opportunity.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that glaciers in Alaska and British Columbia are shrinking is strong and is based on field studies,[56] energy balance models,[59] LIDAR remote sensing,[51,52] and satellite data, especially new lines of evidence from the Gravity Recovery and Climate Experiment (GRACE) satellite.[48,52,55]

Evidence is also strong that Alaska ice mass loss contributes to global sea level rise,[58] with latest results permitting quantitative evaluation of losses globally.[49]

Numerous peer-reviewed publications describe implications of recent increases, but likely longer-term declines, in water input from glacial rivers to reservoirs and therefore hydropower resources.[3,10,65]

Glacial rivers account for 47% of the freshwater input to the Gulf of Alaska[65] and are an important source of organic carbon,[60,61] phosphorus,[62] and iron[63] that contribute to the high productivity of near-shore fisheries.[61,64] Therefore, it is projected that the changes in discharge of glacial rivers will affect ocean circulation patterns and major U.S. and locally significant fisheries.

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

As noted above, major advances from GRACE and other datasets now permit analyses of glacier mass loss that were not possible previously.

Key uncertainties remain related to large year-to-year variation, the spatial distribution of snow accumulation and melt, and the quantification of glacier calving into the ocean and lakes. Although most large glaciated areas of the state are regularly measured observationally, extrapolation to unmeasured areas carries uncertainties due to large spatial variability.

Although there is broad agreement that near-shore circulation in the Gulf of Alaska is influenced by the magnitude of freshwater inputs, little is known about the mechanisms by which near-term increases and subsequent longer-term decreases in glacier runoff (as the glaciers disappear) will affect the structure of the Alaska Coastal Current and smaller-scale ocean circulation, both of which have feedback on fisheries.

The magnitude and timing of effects on hydropower production depend on changes in glacial mass, as described above.

Assessment of confidence based on evidence

High confidence that glacier mass loss in Alaska and British Columbia is high, contributing 20% to 30% as much to sea level rise as does shrinkage of the Greenland Ice Sheet.

High confidence that due to glacier mass loss there will be related impacts on hydropower production, ocean circulation, fisheries, and global sea level rise.

Key message #3 Traceable Account

Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Previous evidence that permafrost is warming[66] has been confirmed and enhanced by more recent studies.[70] The most recent modeling efforts (for example, Avis et al. 2011; Jafarov et al. 2012[71,73]) extend earlier results[72] and project that permafrost will be lost from the upper few meters from large parts of Alaska by the end of this century.

Evidence that permafrost thaw leads to drier landscapes[81,82] is beginning to accumulate, especially as improved remote sensing tools are applied to assess more remote regions.[71]

Satellite data has expanded the capacity to monitor wildfire across the region, providing additional evidence of wildfire extent.[87] This new evidence has led to increased study that is beginning to reveal impacts on ecosystems and wildlife habitat, but much more work is needed to understand the extent of natural resilience.

Impacts of permafrost thaw on the maintenance of infrastructure[11,74,75,76,77] is currently moderate but rapidly accumulating. Evidence that permafrost thaw will jeopardize efforts to offset fossil fuel emissions is suggestive (Ch. 2: Our Changing Climate).[94,100]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

This evidence included results from improved models and updated observational data. The assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm the relevance and significance of the key message for local decision-makers.

Key uncertainties involve: 1) the degree to which increases in evapotranspiration versus permafrost thaw are leading to drier landscapes; 2) the degree to which it is these drier landscapes associated with permafrost thaw, versus more severe fire weather associated with climate change, that is leading to more wildfire; 3) the degree to which the costs of the maintenance of infrastructure are associated with permafrost thaw caused by climate change versus disturbance of permafrost due to other human activities; and 4) the degree to which climate change is causing Alaska to be a sink versus a source of greenhouse gases to the atmosphere.

Assessment of confidence based on evidence

Very high confidence that permafrost is warming.

High confidence that landscapes in interior Alaska are getting drier, although the relative importance of different mechanisms is not completely clear.

Medium confidence that thawing permafrost results in more wildfires. There is **high** confidence that wildfires have been increasing in recent decades, even if it is not clear whether permafrost thaw or hotter and drier weather is more important.

High confidence that climate change will lead to increased maintenance costs in future decades. **Low** confidence that climate change has led to increased maintenance costs of infrastructure in recent decades.

Very high confidence that ecological changes will cause Alaska to become a source of greenhouse gases to the atmosphere, even though evidence that Alaska is currently a carbon source is only suggestive.

Key message #4 Traceable Account

Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10]

Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe evidence that ocean temperatures are rising and ocean chemistry, especially pH, is changing.[10] New observational data from buoys and ships document increasing acidity and aragonite under-saturation (that is, the tendency of calcite and aragonite in shells to dissolve) in Alaskan coastal waters.

Accumulating strong evidence suggests that these changes in ocean temperature and chemistry, including pH, will likely affect major Alaska marine fisheries, although the relative importance of these changes and the exact nature of response of each fishery are uncertain.[101,102,103]

Alaska's commercial fisheries account for roughly 50 percent of the United States' total wild landings. Alaska led all states in both volume and ex-vessel value of commercial fisheries landings in 2009, with a total of 1.84 million metric tons worth $1.3 billion.[1]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

The new evidence included results from improved models and updated observational data. The assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm the relevance and significance of the key message for local decision-makers.

A key uncertainty is what the actual impacts of rising temperatures and changing ocean chemistry, including an increase in ocean acidification, will be on a broad range of marine biota and ecosystems. More monitoring is needed to document the extent and location of changes. Additional research is needed to assess how those changes will affect the productivity of key fishery resources and their food and prey base.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

High confidence of increased ocean temperatures and changes in chemistry.

Medium confidence that fisheries will be affected.

KEY MESSAGE #5 TRACEABLE ACCOUNT

The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence exists in recorded local observational accounts as well as in the peer-reviewed scientific literature of the cumulative effects of climate-related environmental change on Native communities in Alaska; these effects combine with other socioeconomic stressors to strain rural Native communities (Ch. 12: Indigenous Peoples).[124,125,126,131] Increasing attention to impacts of climate change is revealing new aspects, such as impacts to health and hunter safety (for example, Baffrey and Huntington 2010; Brubaker et al. 2011[78,134]). There is also strong evidence for the cultural adaptive capacity of these communities and peoples over time.[91,130,135]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

The precise mechanisms by which climate change affects Native communities are poorly understood, especially in the context of rapid social, economic, and cultural change. Present day responses to environmental change are poorly documented. More research is needed on the ways that Alaska Natives respond to current biophysical climate change and to the factors that enable or constrain contemporary adaptation.

Alaska Native communities are already being affected by climate-induced changes in the physical and biological environment, from coastal erosion threatening the existence of some communities, to alterations in hunting, fishing, and gathering practices that undermine the intergenerational transfer of culture, skill, and wisdom. At the same time, these communities have a long record of adaptation and flexibility. Whether such adaptability is sufficient to address the challenges of climate change depends both on the speed of climate-induced changes and on the degree to which Native communities are supported rather than constrained in the adaptive measures they need to make.[124]

Assessment of confidence based on evidence

There is **high** confidence that cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

Climate Change Impacts in the United States

CHAPTER 23

HAWAI‘I

AND U.S. AFFILIATED PACIFIC ISLANDS

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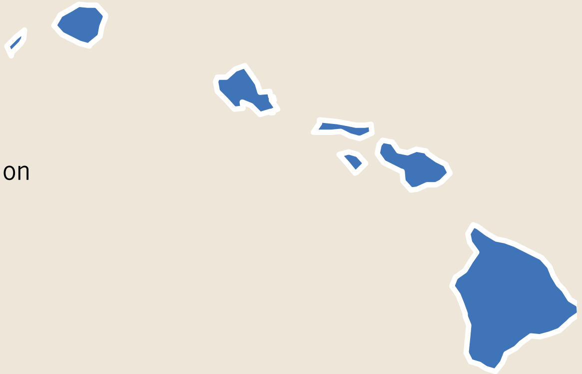

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On the Web: http://nca2014.globalchange.gov/report/regions/hawaii-and-pacific-islands

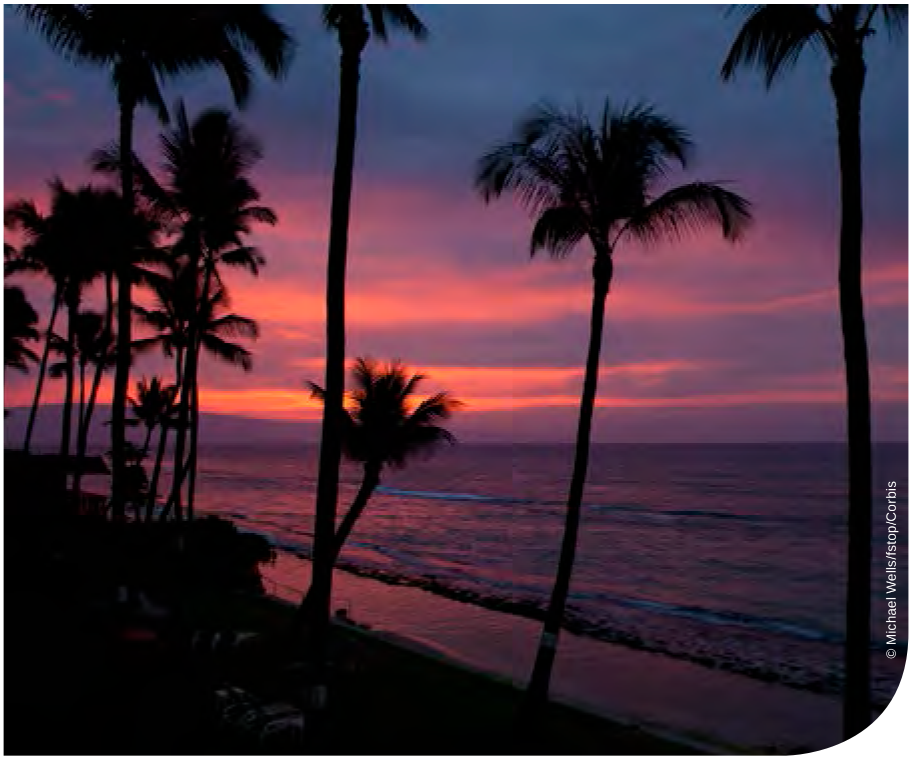
INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

23 HAWAI‘I
AND U.S. AFFILIATED PACIFIC ISLANDS

KEY MESSAGES

1. **Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.**
2. **Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.**
3. **Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.**
4. **Rising sea levels, coupled with high water levels caused by storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.**
5. **Mounting threats to food and water security, infrastructure, health, and safety are expected to lead to increasing human migration, making it increasingly difficult for Pacific Islanders to sustain the region’s many unique customs, beliefs, and languages.**

The U.S. Pacific Islands region (Figure 23.1) is vast, comprising more than 2,000 islands spanning millions of square miles of ocean. The largest group of islands in this region, the Hawaiian Archipelago, is located nearly 2,400 miles from any continental landmass, which makes it one of the most remote archipelagos on the globe.[1] The Hawaiian Islands support fewer than 2 million people, yet provide vital strategic capabilities to U.S. defense – and the islands’ biodiversity is important to the world. Hawai‘i and the U.S. affiliated Pacific Islands are at risk from climate changes that will affect nearly every aspect of life. Rising air and ocean temperatures, shifting rainfall patterns, changing frequencies and intensities of storms and drought, decreasing baseflow in streams, rising sea levels, and changing ocean chemistry will affect ecosystems on land and in the oceans, as well as local communities, livelihoods, and cultures. Low islands are particularly at risk.



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The Pacific Islands include volcanic islands, islands of continental crust, atolls (formed by coral reefs), limestone islands, and islands of mixed geologic origin, with tremendous landscape diversity. In the Hawaiian High Islands, as many as 10 ecozones – from alpine systems to tropical rainforests – exist within a 25 mile span.[3,4] Isolation and landscape diversity in Hawai‘i brings about some of the highest concentrations of native species, found nowhere else in the world.[4] Several U.S. Pacific Islands are marine biodiversity hotspots, with the greatest diversity found in the Republic of Palau, and the highest percentage of native reef fishes in Hawai‘i.[5] These islands provide insights into evolution and adaptation, concepts important for predicting the impacts of climate change on ecosystems. Their genetic diversity also holds the potential for developing natural products and processes for biomedical and industrial use.

U.S. Pacific Islands Region

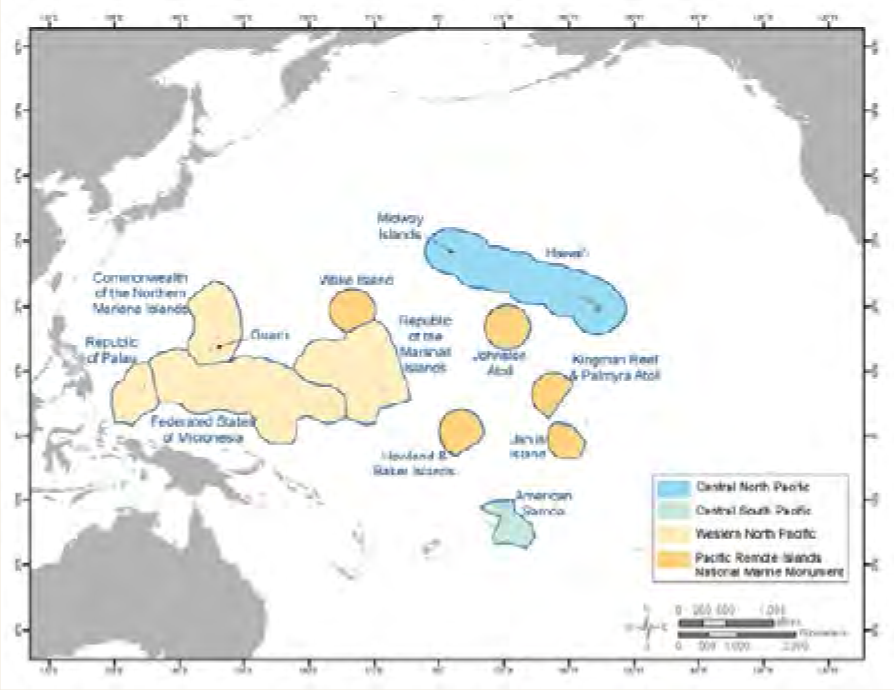

Figure 23.1. The U.S. Pacific Islands region includes our 50th state, Hawai‘i, as well as the Territories of Guam, American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). Citizens of Guam and CNMI are U.S. citizens, and citizens of American Samoa are U.S. nationals. Through the Compacts of Free Association, citizens of RP, FSM, and RMI have the right to travel to the U.S. without visas to maintain “habitual residence” and to pursue education and employment. The map shows three sub-regions used in this assessment and the islands that comprise the Pacific Remote Islands National Monument. Shaded areas indicate each island’s Exclusive Economic Zone (EEZ) (Figure source: Keener et al. 2012[2]).

The Pacific Islands region includes demographically, culturally, and economically varied communities of diverse indigenous Pacific Islanders, intermingled with immigrants from many countries. At least 20 languages are spoken in the region. Pacific Islanders recognize the value and relevance of their cultural heritage and systems of traditional knowledge; their laws emphasize the long-term multigenerational connection with their lands and resources.[6] Tourism contributes prominently to the gross domestic product of most island jurisdictions, as does the large U.S. military presence. Geographic remoteness means that the costs of air transport and shipping profoundly influence island economies. Natural resources are limited, with many communities relying on agriculture and ecosystems (such as coral reefs, open oceans, streams, and forests) for sustenance and revenue.

Key Message 1: Changes to Marine Ecosystems

Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.

Ocean temperatures in the Pacific region exhibit strong year-to-year and decadal fluctuations, but since the 1950s, they have also exhibited a warming trend, with temperatures from the surface to a depth of 660 feet rising by as much as 3.6°F.[7]

Future sea surface temperatures are projected to increase 1.1°F (compared to the 1990 levels) by 2030, 1.8°F by 2055, and 2.5°F by 2090 under a scenario that assumes substantial reductions in emissions (B1), or 1.7°F by 2030, 2.3°F by 2055, and 4.7°F by 2090 under a scenario that assumes continued increases in emissions (A2).[8]

Bleaching events (as a result of higher ocean temperatures) can weaken or kill corals. At least three mass bleaching episodes have occurred in the northwestern Hawaiian Islands in the last decade.[9] Incidences of coral bleaching have been recorded in

“High” and “Low” Pacific Islands Face Different Threats

Figure 23.2. The Pacific Islands include “high” volcanic islands, such as that on the left, that reach nearly 14,000 feet above sea level, and “low” atolls and islands, such as that on the right, that peak at just a few feet above present sea level. (Left) Koʻolau Mountains on the windward side of Oahu, Hawaiʻi (Photo credit: kstrebor via Flickr.com). (Right) Laysan Island, Papahānaumokuākea Marine National Monument (Photo credit: Andy Collins, NOAA).

Micronesia and American Samoa,[10] testing the resilience of these reefs. Coral disease outbreaks have also been reported in the Hawaiian archipelago,[11] American Samoa,[12,13] the Marshall Islands, and Palau,[14] correlated with periods of unusually high water temperatures.[15] Despite uncertainties, advanced modeling techniques project a large decline in coral cover in the Hawaiian Archipelago during this century. However, there are significant differences in the projected time frames and geographic distribution of these declines, even under a single climate change scenario.[16] By 2100, assuming ongoing increases in emissions of heat-trapping gases (A2 scenario), continued loss of coral reefs and the shelter they provide will result in extensive losses in both numbers and species of reef fishes.[17] Even with a substantial reduction in emissions (B1 scenario), reefs could be expected to lose as much as 40% of their reef-associated fish. Coral reefs in Hawaiʻi provide an estimated $385 million in goods and services annually,[18] which could be threatened by these impacts.

Ocean acidification is also taking place in the region, which adds to ecosystem stress from increasing temperatures. Ocean acidity has increased by about 30% since the pre-industrial era and is projected to further increase by 37% to 50% from present levels by 2100 (Ch. 2: Our Changing Climate, Key Message 12).[19] The amount of calcium carbonate, the biologically important mineral critical to reef-building coral and to calcifying algae, will decrease as a result of ocean acidification. By 2035 to 2060, levels of one form of the mineral (aragonite) are projected to decline enough to reduce coral growth and survival around the Pacific, with continuing declines thereafter.[20] Crustose coralline algae, an inconspicuous but important component of reefs that help reefs to form and that act as critical surfaces on which other living things grow, are also expected to exhibit reduced growth and survival.[21,22] Ocean acidification reduces the ability of corals to build reefs and also increases erosion,[23] leading to more fragile reef habitats. These changes are projected to have a strong negative impact on the econo-

EL NIÑO AND OTHER PATTERNS OF CLIMATE VARIABILITY

The Pacific region is subject to various patterns of climate variability. The effects of the El Niño-Southern Oscillation (ENSO) and other patterns of oceanic and atmospheric variability on the region are significant. They include large variations in sea surface temperatures, the strength and persistence of the trade winds, the position of jet streams and storm tracks, and the location and intensity of rainfall.[8,29,30] The ENSO-related extremes of El Niño and La Niña generally persist for 6 to 18 months and change phase roughly every 3 to 7 years.[8,31] The Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) are patterns that operate over even longer time horizons and also influence the weather and climate of the region.[31,32] Such dramatic short-term variability (the “noise”) can obscure the long-term trend (the “signal”).[33] Despite the challenges of distinguishing natural climate variability from climate change, there are several key indicators of observed change that serve as a basis for monitoring and evaluating future change.[2]

mies and well-being of island communities, with loss of coral biodiversity and reduced resilience.[24]

Similarly, there will be large impacts to the economically important tuna fishery in the Pacific Island region. Surface chlorophyll data obtained by satellites indicate less favorable conditions resulting in reduced productivity for tuna in the subtropical South and North Pacific[26] due to warming. This trend is projected to continue under future climate change.[27] One fishery model, coupled with a climate model, forecasts that the overall western and central Pacific fishery catch for skipjack tuna would initially increase by about 19% by 2035, though there would be no change for bigeye tuna. However, by 2100, skipjack catch would decline by 8% and bigeye catch would decline by 27% if emissions continue to rise (A2 scenario); geographic variations are projected within the region.[28]


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Increasing ocean temperature and acidity threaten coral reef ecosystems.

These changes to both corals and fish pose threats to communities, cultures, and ecosystems of the Pacific Islands both directly through their impact on food security and indirectly through their impact on economic sectors including fisheries and tourism.

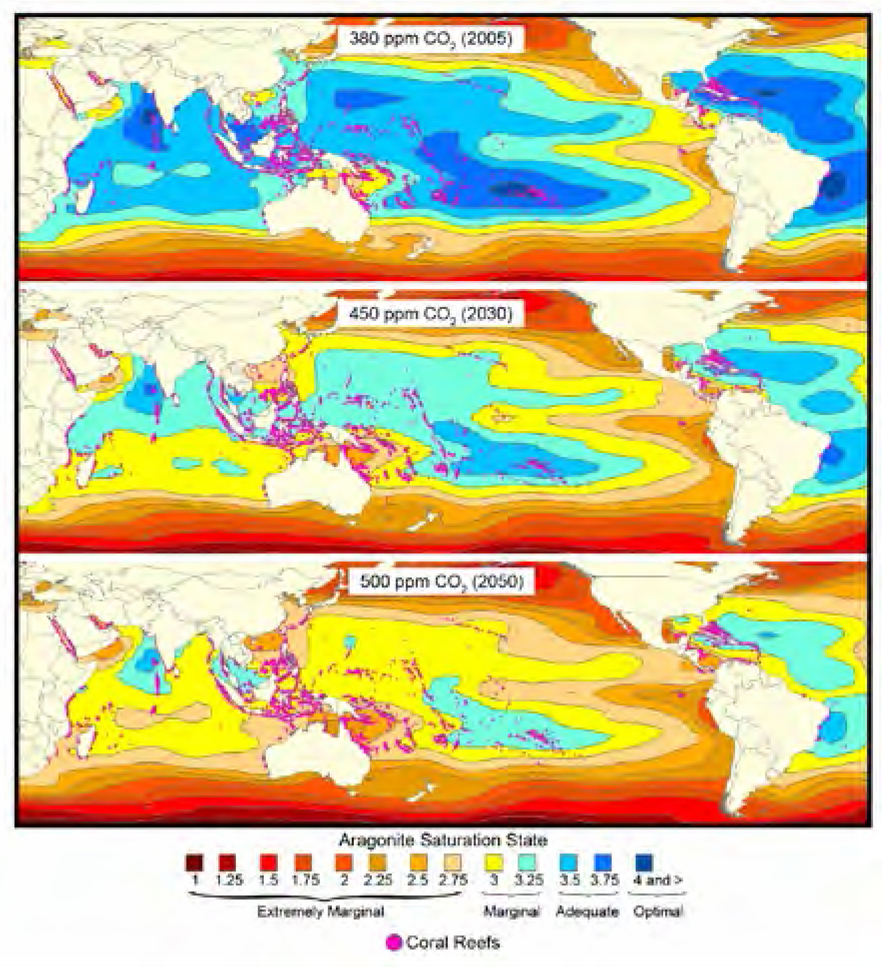
Increased Acidification Decreases Suitable Coral Habitat

Figure 23.3. Ocean waters have already become more acidic from absorbing carbon dioxide from the atmosphere. As this absorption lowers pH, it reduces the amount of calcium carbonate, which is critical for many marine species to reproduce and grow. Maps show projections of the saturation state of aragonite (the form of calcium carbonate used by coral and many other species) if CO_2 levels were stabilized at 380 ppm (a level that has already been exceeded), 450 ppm (middle map), and 500 ppm (bottom map), corresponding approximately to the years 2005, 2030, and 2050, assuming a decrease in emissions from the current trend (scenario A1B). As shown on the maps, many areas that are adequate will become marginal. Higher emissions will lead to many more places where aragonite concentrations are “marginal” or “extremely marginal” in much of the Pacific. (Figure source: Burke et al. 2011[25]).

Key Message 2: Decreasing Freshwater Availability

Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.

In Hawai'i, average precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades, but with high variability due to cyclical climate patterns such as ENSO and the PDO (see "El Niño and other Patterns of Climate Variability").[34,35,36] For the Western North Pacific, a decline of 15% in annual rainfall has been observed in the eastern-most islands in the Micronesia region, and slight upward trends in precipitation have been seen for the western-most islands with high ENSO-related variability.[7] In American Samoa, no trends in average rainfall are apparent, but there is very limited available data.[7,37]

Projections of precipitation are less certain than those for temperature.[2,38] For Hawai'i, a scenario based on statistical downscaling projects a 5% to 10% reduction for the wet season and a 5% increase in the dry season for the end of this century.[39] Projections for late this century from global models for the region give a range of results. Generally they predict annual rainfall to either change little or to increase by up to 5% for the main Hawaiian Islands and to change little or decrease up to 10% in the Northwestern Hawaiian Islands. They also project increases in the Micronesia region (Ch. 2: Our Changing Climate, Figure 2.6),[40] though there is low confidence in all these projections.

Climate change impacts on freshwater resources in the Pacific Islands will vary across the region. Different islands will be affected by different factors, including natural variability patterns that affect storms and precipitation (like El Niño and La Niña events), as well as climate trends that are strongly influenced by specific geographic locations. For example, surface air temperature has increased and is expected to continue to rise over the entire region.[41] In Hawai'i, the rate of increase has been greater at high elevations.[41] In Hawai'i and the Central North Pacific, projected annual surface air temperature increases range from 1.5°F by 2055 (relative to 1971-2000) under a scenario of substantial emissions reduction (B1), to 3.5°F assuming continued increases in emissions (A2).[40,42] In the Western North Pacific, the projected increases by 2055 are 1.9°F for the B1 scenario and 2.6°F for the A2 scenario.[8] In the central South Pacific, projected annual surface air temperature increases by 2055 are 1.9°F (B1) and 2.5°F (A2).[8]

On most islands, increased temperatures coupled with decreased rainfall and increased drought will reduce the amount of freshwater available for drinking and crop irrigation.[43] Climate change impacts on freshwater resources in the region will also vary because of differing island size and topography, which affect water storage capability and susceptibility to coastal flooding. Low-lying islands will be particularly vulnerable due to their small land mass, geographic isolation, limited potable water sources, and limited agricultural resources.[44] Also, as sea level rises over time, increasing saltwater intrusion from the ocean during storms will exacerbate the situation (Figure 23.6).[45,46] These are only part of a cascade of climate change related impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities.[47]

Observed Changes in Annual Rainfall in the Western North Pacific

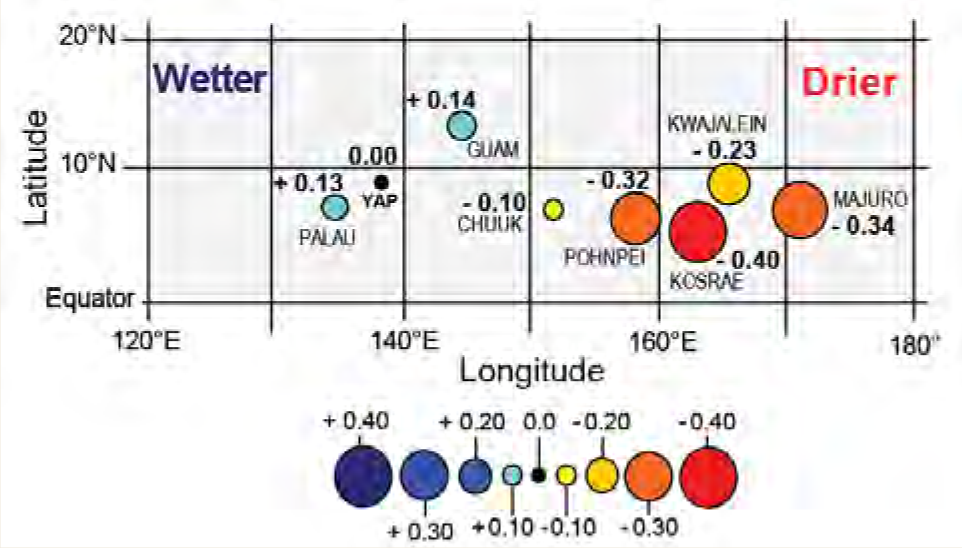

Figure 23.4. Islands in the western reaches of the Pacific Ocean are getting slightly more rainfall than in the past, while islands more to the east are getting drier (measured in change in inches of monthly rainfall per decade over the period 1950-2010). Darker blue shading indicates that conditions are wetter, while darker red shading indicates drier conditions. The size of the dot is proportional to the size of the trend on the inset scale. (Figure source: Keener et al. 2012[2]).

Key Message 3: Increased Stress on Native Plants and Animals

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.

Projected climate changes will significantly alter the distribution and abundance of many native marine, terrestrial, and freshwater species in the Pacific Islands. The vulnerability of coral reef and ocean ecosystems was discussed earlier. Land-based and freshwater species that exist in high-elevation ecosystems in high islands, as well as low-lying coastal ecosystems on all islands, are especially vulnerable. Existing climate zones on high islands are generally projected to shift upslope in response to climate change.[48] The ability of native species to adapt to shifting habitats will be affected by ecosystem discontinuity and fragmentation, as well as the survival or extinction of pollinators and seed dispersers. Some (perhaps many) invasive plant species will have a competitive edge over native species, as they disproportionately benefit from increased carbon dioxide, disturbances from extreme weather and climate events, and an ability to invade higher elevation habitats as climates warm.[49] Hawaiian high-elevation alpine ecosystems on Hawai‘i and Maui islands are already beginning to show strong signs of higher temperatures and increased drought.[50] For example, the number of Haleakalā silversword, a rare plant that is an integral component of the alpine ecosystem in Haleakalā National Park in Maui and is found nowhere else on the planet, has declined dramatically over the past two decades.[51] Many of Hawai‘i’s native forest birds, marvels of evolution largely limited to high-elevation forests due to predators and diseases, are increasingly vulnerable as rising temperatures allow mosquitoes carrying diseases like avian malaria to thrive at higher elevations and thereby reduce the extent of safe bird habitat.[48,52]

Native Plants at Risk

Figure 23.5. Warming at high elevations could alter the distribution of native plants and animals in mountainous ecosystems and increase the threat of invasive species. The threatened, endemic ‘ahinahina, or Haleakalā silversword (*Argyroxiphium sandwicense subsp. macrocephalum*), shown here in full bloom on Maui, Hawaiian Islands, is one example. (Photo credit: Forest and Kim Starr).

On high islands like Hawai‘i, decreases in precipitation and baseflow are already indicating impacts on freshwater ecosystems and aquatic species.[35,37] Many Pacific Island freshwater fishes and invertebrates have oceanic larval stages in which they seasonally return to high island streams to aid reproduction.[53] Changes in stream flow and oceanic conditions that affect larval growth and survival will alter the ability of these species to maintain viable stream populations.

Key Message 4: Sea Level Rising

Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.

Global average sea level has risen by about 8 inches since 1900,[54] with recent satellite observations indicating an increased rate of rise over the past two decades (1.3 inches per decade) (see also Ch. 2: Our Changing Climate, Key Message 10).[55] Recent regional sea level trends in the western tropical Pacific are higher[56,57] than the global average, due in part to changing wind patterns associated with natural climate variability.[58,59] Over this century, sea level in the Pacific is expected to rise at about the same rate as the projected increase in global average sea level, with regional variations associated with ocean circulation changes and the Earth’s response to other large-scale changes, such as melting glaciers and ice sheets as well as changing water storage in lakes and reservoirs.[60,61] For the region, extreme sea level events generally occur when high tides combine with changes in water levels due to storms, ENSO (see “El Niño and other Patterns of Climate Variability”), and other variations.[54,55,56,57,58,59,60]

Rising sea levels will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, shallow coral reefs, sea grass beds, intertidal flats and mangrove forests, and other social, eco-

Saltwater Intrusion Destroys Crops

Figure 23.6. Taro crops destroyed by encroaching saltwater at Lukunoch Atoll, Chuuk State, FSM. Giant swamp taro is a staple crop in Micronesia that requires a two- to three-year growing period from initial planting to harvest. After a saltwater inundation from a storm surge or very high tide, it may take two years of normal rainfall to flush brackish water from a taro patch, resulting in a five-year gap before the next harvest if no further saltwater intrusion takes place. (Photo credit: John Quidachay, USDA Forest Service).

Residents of Low-lying Islands at Risk

Figure 23.7. Republic of the Marshall Islands, with a land area of just 1.1 square miles and a maximum elevation of 10 feet, may be among the first to face the possibility of climate change induced human migration as sea level continues to rise. (Photo credit: Darren Nakata).

nomic, and natural resources. Impacts will vary with location depending on how regional sea level variability combines with increases of global average sea level.[62] On low islands, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and periodic flooding increases the salinity of groundwater. Coastal and nearshore environments will progressively be affected as sea levels rise and high wave events alter low islands' size and shape. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10% to 20% in total regional mangrove area over the next century.[63] This would in turn reduce the nursery areas and feeding grounds for fish species, habitat for crustaceans and invertebrates, shoreline protection and wave dampening, and water filtration provided by mangroves.[64] Pacific seabirds that breed on low-lying atolls will lose large segments of their breeding populations[65] as their habitat is increasingly and more extensively covered by seawater.

Impacts to the built environment on low-lying portions of high islands, where nearly all airports are located and where each island's road network is sited,[66] will be nearly as profound as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. In Hawai‘i, for example, where tourism comprises 26% of the state's economy, damage to tourism infrastructure could have large economic impacts –the loss of Waikīkī Beach alone could lead to an annual loss of $2 billion in visitor expenditures.[67]

Higher Sea Level Rise in Western Pacific

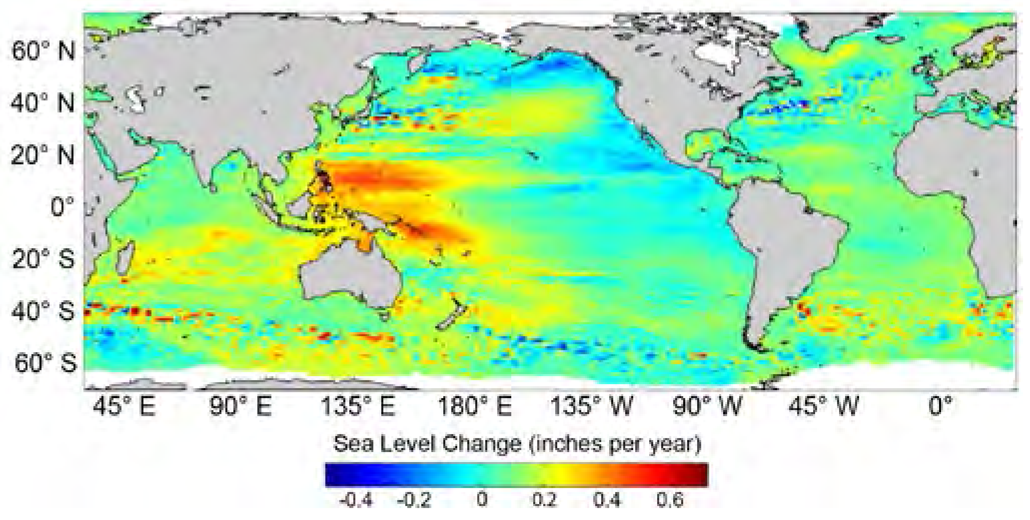

Figure 23.8. Map shows large variations across the Pacific Ocean in sea level trends for 1993-2010. The largest sea level increase has been observed in the western Pacific. (Figure source: adapted from Merrifield 2011[57] by permission of American Meteorological Society).

Key Message 5: Threats to Lives, Livelihoods, and Cultures

Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites, making it increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.

All of the climate change impacts described above will have an impact on human communities in Pacific Islands. Because Pacific Islands are almost entirely dependent upon imported food, fuel, and material, the vulnerability of ports and airports to extreme events, sea level rise, and increasing wave heights is of great concern. Climate change is expected to have serious effects on human health, for example by increasing the incidence of dengue fever (Ch. 9: Human Health).[68] In addition, sea level rise and flooding are expected to overwhelm sewer systems and threaten public sanitation.

The traditional lifestyles and cultures of indigenous communities in all Pacific Islands will be seriously affected by climate change (see also Chapter 12: Indigenous Peoples). Sea level rise and associated flooding is expected to destroy coastal artifacts and structures[69] or even the entire land base associated with cultural traditions.[70] Drought threatens traditional food sources such as taro and breadfruit, and coral death from warming-induced bleaching will threaten subsistence fisheries in island communities.[46] Climate change related environmental deterioration for communities at or near the coast, coupled with other socioeconomic or political motivations, is expected to lead individuals, families, or communities to consider moving to new locations. Depending on the scale and distance of the migration, a variety of challenges face the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth.

Adaptation Activities

Adaptive capacity in the region varies and reflects the histories of governance, the economies, and the geographical features of the island/atoll site. High islands can better support larger populations and infrastructure, attract industry, foster institutional growth, and thus bolster adaptive capacity;[2] but these sites have larger policy or legal hurdles that complicate coastal planning.[71] Low islands have a different set of challenges. Climate change related migration, for example, is particularly relevant to the low island communities in the Republic of the Marshall Islands (RMI) and the Federated States of Micronesia (FSM), and presents significant practical, cultural, and legal challenges.[72]

In Hawai‘i, state agencies have drafted a framework for climate change adaptation by identifying sectors affected by climate change and outlining a process for coordinated statewide adaptation planning.[73] Both Hawai‘i and American Samoa specifically consider climate change in their U.S. Federal Emergency Management Agency (FEMA) hazard mitigation plans, and the Commonwealth of Northern Mariana Islands lists climate variability as a possible hazard related to extreme climate events.[74] The U.S. Pacific Island Freely Associated States (which includes the Republic of Palau, FSM, and RMI; Figure 23.1) have worked with regional organizations to develop plans and access international resources. Each of these jurisdictions has developed a status report on integrating climate-related hazard information in disaster risk reduction planning and has developed plans for adaptation to climate-related disaster risks.[75] Overall, there is very little research on the effectiveness of alternative adaptation strategies for Pacific Islands and their communities. The regional culture of communication and collaboration provides a strong foundation for adaptation planning and will be important for building resilience in the face of the changing climate.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the assessment process was convening three focus area workshops as part of the Pacific Islands Regional Climate Assessment (PIRCA). The PIRCA is a collaborative effort aimed at assessing the state of climate knowledge, impacts, and adaptive capacity in Hawai‘i and the U.S. Affiliated Pacific Islands. These workshops included representatives from the U.S. federal agencies, universities, as well as international participants from other national agencies and regional organizations. The workshops led to the formulation of a foundational Technical Input Report (TIR).[2] The report consists of nearly 140 pages, with almost 300 references, and was organized into 5 chapters by 11 authors.

The chapter author team engaged in multiple technical discussions via regular teleconferences that permitted a careful review of the foundational TIR[2] and of approximately 23 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions included a face-to-face meeting held on July 9, 2012. These discussions were supported by targeted consultation among the lead and contributing authors of each message. There were several iterations of review and comment on draft key messages and associated content.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.

Description of evidence base

The key message was chosen based on input from the extensive evidence documented in the Hawai‘i Technical Input Report[2] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Ocean warming: There is ample evidence that sea-surface temperatures have already risen throughout the region based on clear observational data, with improved data with the advent of satellite and in situ (ARGO & ship-based) data.[7] Assessment of the literature for the region by other governmental bodies (such as Australian Bureau of Meteorology [ABOM] and the Commonwealth Scientific and Industrial Research Organization [CSIRO]) point to continued increases under both B1 and A2 scenarios.[8]

Ocean acidification: Globally, the oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually, and becoming more acidic as a result (Ch. 2: Our Changing Climate, Key Message 12). Historical and current observations of aragonite saturation state (Ωar) for the Pacific Ocean show a decrease from approximately 4.9 to 4.8 in the Central North Pacific (Hawaiian Islands); in the Western North Pacific (Republic of Marshall Islands, Commonwealth of Northern Mariana Islands, Federated States of Micronesia, Republic of Palau, Guam), it has declined from approximately 4.5 to 3.9 in 2000, and to 4.1 in the Central South Pacific (American Samoa) (this chapter: Figure 23.3; Ch. 24: Oceans and Marine Resources).[19] Projections from CMIP3 models indicate the annual maximum aragonite saturation state will reach values below 3.5 by 2035 in the waters of the Republic of the Marshall Islands (RMI), by 2030 in the Federated States of Micronesia (FSM), by 2040 in Palau, and by 2060 around the Samoan archipelago. These values are projected to continue declining thereafter.[2] The recently published *Reefs at Risk Revisited*[25] estimates aragonite saturation state (as an indicator of ocean acidification) for CO_2 stabilization levels of 380 ppm, 450 ppm, and 500 ppm, which correspond approximately to the years 2005, 2030, and 2050 under the A1B emissions scenario (which assumes similar emissions to the A2 scenario through 2050 and a slow decline thereafter) (Figure 4.4 from Keener et al. 2012[2]).

Bleaching events: These have been well-documented in extensive literature worldwide due to increasing temperatures, with numerous studies in Hawai‘i and the Pacific Islands.[9,10]

Disease outbreaks: Reports of coral diseases have been proliferating in the past years,[11,13] but few have currently been adequately described, with causal organisms identified (for example, fulfill Koch's Postulates).

Reduced growth: There is abundant evidence from laboratory experiments that lower seawater pH reduces calcification rates in marine organisms (for example, Feely et al. 2009[19]). However, actual measurements on the effects of ocean acidification on coral reef ecosystems in situ or in complex mesocosms are just now becoming available, and these measurements show that there are large regional and diel variability in pH and pCO_2.[76] The role of diel and regional variability on coral reef ecosystems requires further investigation.

Distribution patterns of coastal and ocean fisheries: Evidence of the effects of ocean acidification on U.S. fisheries in Hawai‘i and the Pacific Islands is currently limited (Lehodey et al. 2011)[28] but there is accumulating evidence for ecosystem impacts.

New information and remaining uncertainties

New information: Since the 2009 National Climate Assessment,[77] considerable effort has been employed to understand the impacts of ocean acidification (OA) on marine ecosystems, including recent ecosystem-based efforts.[22,28] Studies of OA impacts on organisms has advanced considerably, with careful chemistry using worldwide standard protocols making inroads into understanding a broadening range of organisms.

However, predicting the effect of ocean acidification on marine organisms and marine coral reef ecosystems remains the key issue of uncertainty. The role of community metabolism and calcification in the face of overall reduction in aragonite saturation state must be investigated.

Understanding interactions between rising temperatures and OA remains a challenge. For example, high temperatures simultaneously cause coral bleaching, as well as affect coral calcification rates, with both impacts projected to increase in the future.

Assessment of confidence based on evidence

There is **very high** confidence that ocean acidification and decreased aragonite saturation is taking place and is projected to continue. There is **high** confidence that ocean warming is taking place and is projected to continue; there is **medium** confidence that the thermal anomalies will lead to continued coral bleaching and coral disease outbreaks.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.

Description of evidence base

There is abundant and definitive evidence that air temperature has increased and is projected to continue to increase over the entire region,[8,41,78] as there is globally (Ch. 2: Our Changing Climate, Key Message 3).

In Hawai‘i and the Central North Pacific (CNP), projected annual surface air temperature increases are 1.0°F to 2.5°F by 2035, relative to 1971-2000.[40,42] In the Western North Pacific (WNP), the projected increases are 2.0°F to 2.3°F by 2030, 6.1°F to 8.5°F by 2055, and 4.9°F to 9.2°F by 2090.[8] In the central South Pacific (CSP), projected annual surface air temperature increases are 1.1°F to 1.3°F by 2030, 1.8°F to 2.5°F by 2055, and 2.5°F to 4.9°F by 2090.[8] (Please note that the islands that comprise the U.S. Pacific Islands Region are shown in Figure 23.1).

In Hawai‘i, mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high variability related to El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).[34,35] For the WNP, a decline of 15% in annual rainfall has been observed in the eastern-most islands in the Micronesia region and slight upward trends in precipitation have been seen for the western-most islands, with high ENSO-related variability.[8] In American Samoa, no trends in average rainfall are apparent based on the very limited available data.[8,37]

For the region as a whole, models disagree about projected changes in precipitation. Mostly models predict increases in mean annual rainfall and suggest a slight dry season decrease and wet season increase in precipitation.[8] However, based on statistical downscaling, one study[39] projected a 5% to 10% reduction in precipitation for the wet season and a 5% increase in the dry season for Hawai‘i by the end of this century.

On most islands, increased temperatures coupled with decreased rainfall and increased drought will reduce the amount of freshwater for drinking and crop irrigation.[43] Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, and limited potable water sources and agricultural resources.[44] The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time (Key Message 4, this chapter; Ch. 2: Our Changing Climate, Key Message 10).[2]

New information and remaining uncertainties

Climate change impacts on freshwater resources in the Pacific Islands region will vary because of differing island size and height, which affect water storage capability and susceptibility to coastal inundation. The impacts will also vary because of natural phase variability (for example, ENSO and PDO) in precipitation and storminess (tropical and extra-tropical storms) as well as long-term trends, both strongly influenced by geographic location.

Climate model simulations produce conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change.

Assessment of confidence based on evidence

Freshwater systems are inherently fragile in many Pacific Islands. Historical observations show strong evidence of a decreasing trend for rainfall in Hawai‘i and many other Pacific Islands (Ch. 2: Our Changing Climate).[2] There is abundant and definitive evidence that air temperature has increased and will continue to increase. All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. Based on the evidence base and remaining uncertainties, we have **high** confidence in the key message.

Key message #3 Traceable Account

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.

Description of evidence base

In Hawai‘i and the Central North Pacific (CNP), projected annual surface air temperature increases are 1.0°F to 2.5°F by 2035, relative to 1971-2000.[40,42] In the Western North Pacific (WNP), the projected increases are 2.0°F to 2.3°F by 2030, 6.1°F to 8.5°F by 2055, and 4.9°F to 9.2°F by 2090.[8] In the Central South Pacific (CSP), projected annual surface air temperature increases are 1.1°F to 1.3°F by 2030, 1.8°F to 2.5°F by 2055, and 2.5°F to 4.9°F by 2090.[8] In Hawai‘i the rate of increase has been greater at high elevations.[41] (Please note that the islands that comprise the U.S. Pacific Islands Region are shown in Figure 23.1).

In Hawai‘i mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high ENSO and PDO-related variability.[34,35,36] Projects based on statistical downscaling[39] suggest the most likely precipitation scenario for Hawai‘i for the 21st century to be a 5% to 10% reduction for the wet season and a 5% increase in the dry season.

On high islands like Hawai‘i, decreases in precipitation and baseflow[35] are already indicating that there will be impacts on freshwater ecosystems and aquatic species, and on water-intensive sectors such as agriculture and tourism.

Hawaiian high-elevation alpine ecosystems on Hawai‘i and Maui islands are already beginning to show strong signs of increased drought and warmer temperatures.[50] Demographic data for the Haleakalā silversword, a unique (endemic to upper Haleakalāvolcano) and integral component of the alpine ecosystem in Haleakalā National Park, Maui, have recorded a severe decline in plant numbers over the past two decades.[51] Many of Hawai‘i’s endemic forest birds, marvels of evolution largely limited to high-elevation forests by predation and disease, are increasingly vulnerable as rising temperatures allow the disease-vectoring mosquitoes to thrive upslope and thereby reduce the extent of safe bird habitat.[48,52]

New information and remaining uncertainties

Climate change impacts in the Pacific Islands region will vary because of differing island size and height. The impacts will also vary because of natural phase variability (for example, El Niño-Southern Oscillation and Pacific Decadal Oscillation) in precipitation and storminess (tropical and extra-tropical storms) as well as long-term trends, both strongly influenced by geographic location.

Climate model simulations produce conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change.[2,8]

Climate change ecosystem response is poorly understood.[2]

Assessment of confidence based on evidence

Terrestrial and marine ecosystems are already being impacted by local stressors, such as coastal development, land-based sources of pollution, and invasive species.[2,25] There is abundant and definitive evidence that air temperature has increased and will continue to increase. Historical observations show strong evidence of a decreasing trend for rainfall in Hawai‘i and many other Pacific Islands.[2] Given the evidence base and remaining uncertainties, confidence is **high** in this key message.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.

Description of evidence base

All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. Recent studies give higher sea level rise projections than those projected in 2007 by the Intergovernmental Panel on Climate Change[29] for the rest of this century (Ch. 2: Our Changing Climate, Key Message 10).[55]

Sea level is rising and is expected to continue to rise. Over the past few decades, global mean sea level, as measured by satellite altimetry, has been rising at an average rate of twice the estimated rate for the previous century, based on tide gauge measurements,[55] with models suggesting that global sea level will rise significantly over the course of this century. Regionally, the highest increases have been observed in the western tropical Pacific.[56] However, the current high rates of regional sea level rise in the western tropical Pacific are not expected to persist, as regional sea level will fall in response to a change in phase of natural variability.[62] Regional variations in sea level at interannual and interdecadal time scales are generally attributed to changes in prevailing wind patterns associated with El Niño-Southern Oscillation (ENSO) as well as the Pacific Decadal Oscillation (PDO) and low frequency components of the Southern Oscillation Index (SOI).[59]

For the region, extreme sea level events generally occur when high tides combine with some non-tidal residual change in water level. In the major typhoon zones (Guam and Commonwealth of the Northern Mariana Islands), storm-driven surges can cause coastal flooding and erosion regardless of tidal state. Wave-driven inundation events are a major concern for all islands in the region. At present, trends in extreme levels tend to follow trends in mean sea level.

Increasing mean water levels and the possibility of more frequent extreme water level events, and their manifestation as flooding and erosion, will threaten coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Impacts will vary with location, depending on how natural sea level variability combines with modest increases of mean levels.[62]

On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable.[62] Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and episodic inundation increases salinity of groundwater resources. Impacts to the built environment on low-lying portions of high islands will be much the same as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. One report stated: “Our analyses estimate that nearly $2.0 billion in overall visitor expenditures could be lost annually due to a complete erosion of Waikīkī Beach.”[67]

Coastal and nearshore environments (sandy beaches, shallow coral reefs, seagrass beds, intertidal flats, and mangrove forests) and the vegetation and terrestrial animals in these systems will progressively be affected as sea level rise and high wave events alter atoll island size and shape and reduce habitat features necessary for survival. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10%–20% of total regional mangrove area over the next century.[63] Further, atoll-breeding Pacific seabirds will lose large segments of their breeding populations[65] as their habitat is increasingly and more extensively inundated.

Major uncertainties

Sea levels in the Pacific Ocean will continue to rise with global sea level. Models provide a range of predictions, with some suggesting that global warming may raise global sea level considerably over the course of this century. The range of predictions is large due in part to unresolved physical understanding of various processes, notably ice sheet dynamics.

Changes in prevailing wind patterns associated with natural climate cycles such as ENSO and the PDO affect regional variations in sea level at interannual and interdecadal time scales. Sea level at specific locales will continue to respond to changes in phase of these natural climate cycles. The current high rates of regional sea level rise in the western tropical Pacific are not expected to persist over time, falling once the trade winds begin to weaken.

Future wind wave conditions are difficult to project with confidence given the uncertainties regarding future storm conditions.

Assessment of confidence based on evidence

Evidence for global sea level rise is strong (Ch. 25: Coasts; Ch. 2: Our Changing Climate). Confidence is therefore **very high**. Modeling studies have yielded conflicting results as to how ENSO and other climate modes will vary in the future. As a result, there is **low** confidence in the prediction of future climate states and their subsequent influence on regional sea level.[62] Recent assessments of future extreme conditions generally place **low** confidence on region-specific projections of future storminess.[61]

For aspects of the key message concerning impacts, confidence is **high**.

Key message #5 Traceable Account

Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites, making it increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.

Description of evidence base

Climate change threatens communities, cultures, and ecosystems of the Pacific Islands both directly through impact on food and water security, for example, as well as indirectly through impacts on economic sectors including fisheries and tourism.

On most islands, increased temperatures, coupled with decreased rainfall and increased drought, will lead to an additional need for freshwater resources for drinking and crop irrigation.[43] This is particularly important for locations in the tropics and subtropics where observed data and model projections suggest that, by the end of this century, the average growing season temperatures will exceed the most extreme seasonal temperatures recorded from 1900 to 2006. Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, and limited potable water sources and agricultural resources.[44] The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time. These are but part of a cascade of impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities.[47] On high islands like Hawai‘i, decreases in precipitation and baseflow[35] are already indicating that there will be impacts on freshwater ecosystems and aquatic species and on water-intensive sectors such as agriculture and tourism.

Increasing mean oceanic and coastal water levels and the possibility of more frequent extreme water level events with flooding and erosion will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Impacts will vary with location depending on how natural sea level variability combines with modest increases of mean levels.[62] On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and episodic inundation increases salinity of groundwater resources.

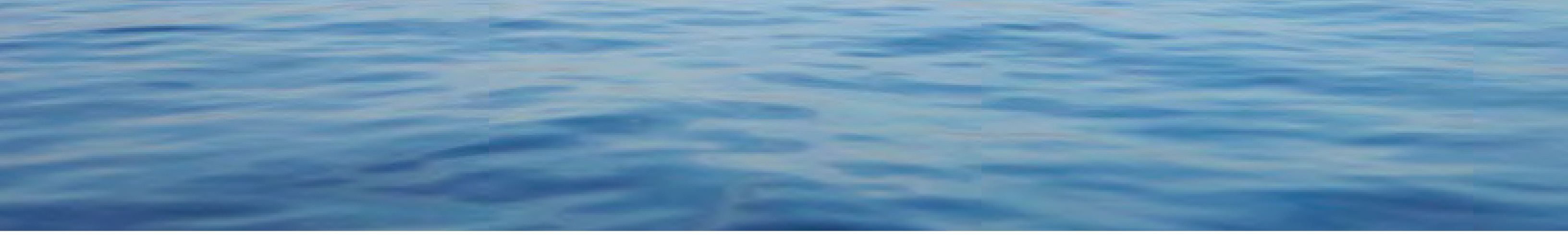
With respect to cultural resources, impacts will extend from the loss of tangible artifacts and structures[69] to the intangible loss of a land base and the cultural traditions that are associated with it.[70]

New information and remaining uncertainties

Whenever appraising threats to human society, it is uncertain the degree to which societies will successfully adapt to limit impact. For island communities, though, the ability to migrate is very limited, and the ability to adapt is especially limited. Depending on the scale and distance of the migration, a variety of challenges face the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth.

Assessment of confidence based on evidence

Evidence for climate change and impacts is strong, but highly variable from location to location. One can be highly confident that climate change will continue to pose varied threats in the region. Adaptive capacity is also highly variable among the islands, so the resulting situation will play out differently in different places. Confidence is therefore **medium**.



Climate Change Impacts in the United States

CHAPTER 24
OCEANS AND MARINE RESOURCES

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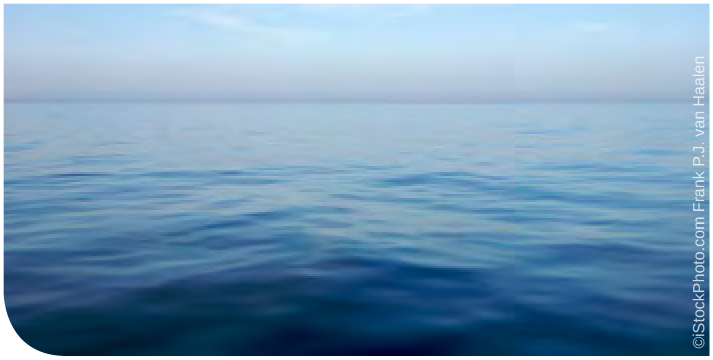
24 OCEANS AND MARINE RESOURCES

KEY MESSAGES

1. **The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.**
2. **The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.**
3. **Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.**
4. **Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and marine life, including corals, abalones, oysters, fishes, and marine mammals.**
5. **Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.**
6. **In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.**

As a nation, we depend on the oceans for seafood, recreation and tourism, cultural heritage, transportation of goods, and, increasingly, energy and other critical resources. The U.S. Exclusive Economic Zone extends 200 nautical miles seaward from the coasts, spanning an area about 1.7 times the land area of the continental U.S. and encompassing waters along the U.S. East, West, and Gulf coasts, around Alaska and Hawai'i, and including the U.S. territories in the Pacific and Caribbean. This vast region is host to a rich diversity of marine plants and animals and a wide range of ecosystems, from tropical coral reefs to Arctic waters covered with sea ice.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Oceans support vibrant economies and coastal communities with numerous businesses and jobs. More than 160 million people live in the coastal watershed counties of the United States, and population in this zone is expected to grow in the future. The oceans help regulate climate, absorb carbon dioxide (an important greenhouse, or heat-trapping, gas), and strongly influence weather patterns far into the continental interior. Ocean issues touch all of us in both direct and indirect ways.[1,2,3]

Changing climate conditions are already affecting these valuable marine ecosystems and the array of resources and services we derive from the sea. Some climate trends, such as rising seawater temperatures and ocean acidification, are common across much of the coastal areas and open ocean worldwide. The biological responses to climate change often vary from region to region, depending on the different combinations of species, habitats, and other attributes of local systems. Data records for the ocean are often shorter and less complete than those on land, and for many biological variables it is still difficult to discern long-term ocean trends from natural variability.[4]

Key Message 1: Rising Ocean Temperatures

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Cores from corals, ocean sediments, ice records, and other indirect temperature measurements indicate the recent rapid increase of ocean temperature is the greatest that has occurred in at least the past millennium and can only be reproduced by climate models with the inclusion of human-caused sources of heat-trapping gas emissions.[5,6] The ocean is a critical reservoir for heat within Earth's climate system, and because of seawater's large heat storing capacity, small changes in ocean temperature reflect large changes in ocean heat storage. Direct measurements of ocean temperatures show warming beginning in about 1970 down to at least 2,300 feet, with stronger warming near the surface leading to increased thermal stratification (or layering) of the water column.[7,8] Sea surface temperatures in the North Atlantic and Pacific, including near U.S. coasts, have also increased since 1900.[9,10] In conjunction with a warming climate, the extent and thickness of Arctic sea ice has decreased rapidly over the past four decades.[11,12] Models that best match historical trends project seasonally ice-free northern waters by the 2030s.[13]

Climate-driven warming reduces vertical mixing of ocean water that brings nutrients up from deeper water, leading to potential impacts on biological productivity. Warming and altered ocean circulation are also expected to reduce the supply of oxygen to deeper waters, leading to future expansion of sub-surface low-oxygen zones.[15] Both reduced nutrients at the surface and reduced oxygen at depth have the potential to change ocean productivity.[14] Satellite observations indicate that warming of the upper ocean on year-to-year timescales leads to reductions in the biological productivity of tropical and subtropical (the region just outside the tropics) oceans and expansion of the area of surface waters with very low quantities of phytoplankton (microscopic marine plants) biomass.[16] Ecosystem models suggest that the same patterns of productivity change will occur over the next century as a consequence of warming during this century, perhaps also with increasing productivity near the poles.[17] These changes can affect ecosystems at multiple levels of the food web, with consequent changes for fisheries and other important human activities that depend on ocean productivity.[4,18]

Observed Ocean Warming

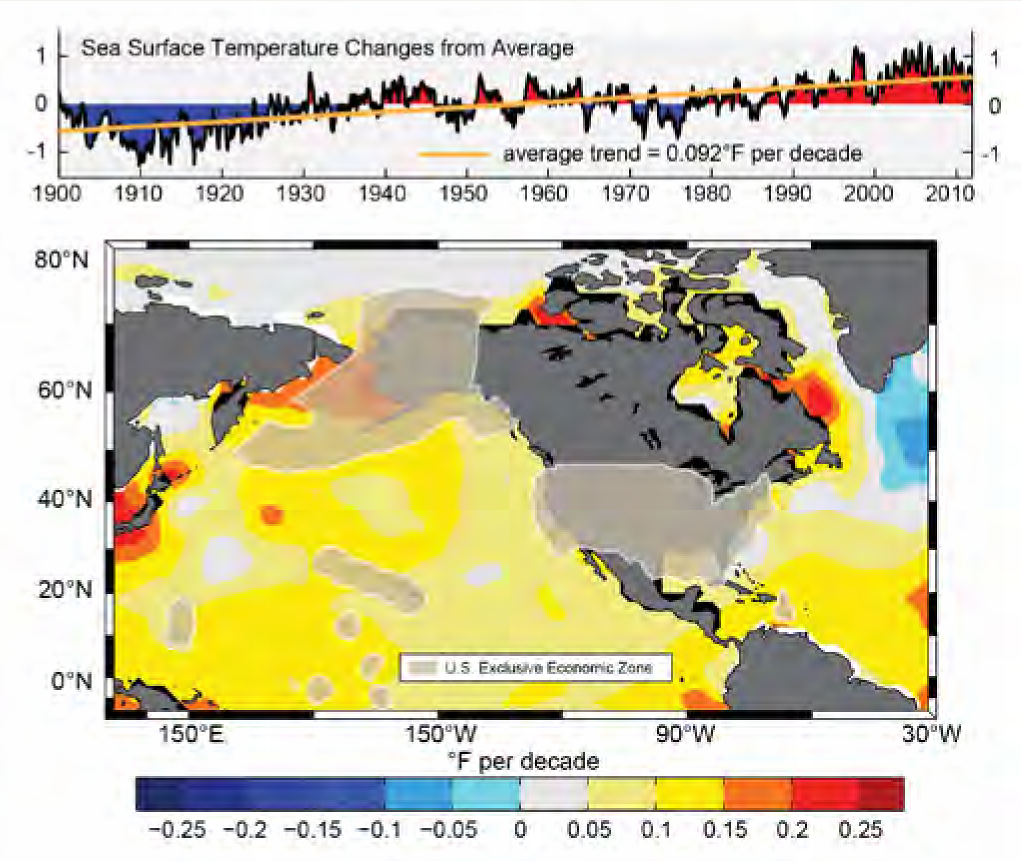


Figure 24.1. Sea surface temperatures for the ocean surrounding the U.S. and its territories have warmed by more than 0.9°F over the past century (top panel). There is significant variation from place to place, with the ocean off the coast of Alaska, for example, warming far more rapidly than other areas (bottom panel). The gray shading on the map denotes U.S. land territory and the regions where the U.S. has rights over the exploration and use of marine resources, as defined by the U.S. Exclusive Economic Zone (EEZ). (Figure source: adapted from Chavez et al. 2011[14]).

Other changes in the physical and chemical properties of the ocean are also underway due to climate change. These include rising sea level,[19] changes in upper ocean salinity (including reduced salinity of Arctic surface waters) resulting from altered inputs of freshwater and losses from evaporation, changes in wave height from changes in wind speed, and changes in oxygen content at various depths – changes that will affect marine ecosystems and human uses of the ocean in the coming years.[4]

While the long-term global pattern is clear, there is considerable variability in the effects of climate change regionally and locally because oceanographic conditions are not uniform and are strongly influenced by natural climate fluctuations. Trends during short periods of a decade or so can be dominated by natural variability.[25] For example, the high incidence of La Niña events in the last 15 years has played a role in the observed temperature trends.[26]

Analyses[27] suggest that more of the increase in heat energy during this period has been transferred to the deep ocean (see also Ch. 2: Our Changing Climate). While this might temporarily slow the rate of increase in surface air temperature, ultimately it will prolong the effects of global warming because the oceans hold heat for longer than the atmosphere does.

Interactions with processes in the atmosphere and on land, such as rainfall patterns and runoff, also vary by region and are strongly influenced by natural climate fluctuations, resulting in additional local variation in the observed effects in the ocean.

Marine ecosystems are also affected by other human-caused local and regional disturbances such as overfishing, coastal habitat loss, and pollution, and climate change impacts may exacerbate the effects of these other human factors.

Ocean Impacts of Increased Atmospheric Carbon Dioxide

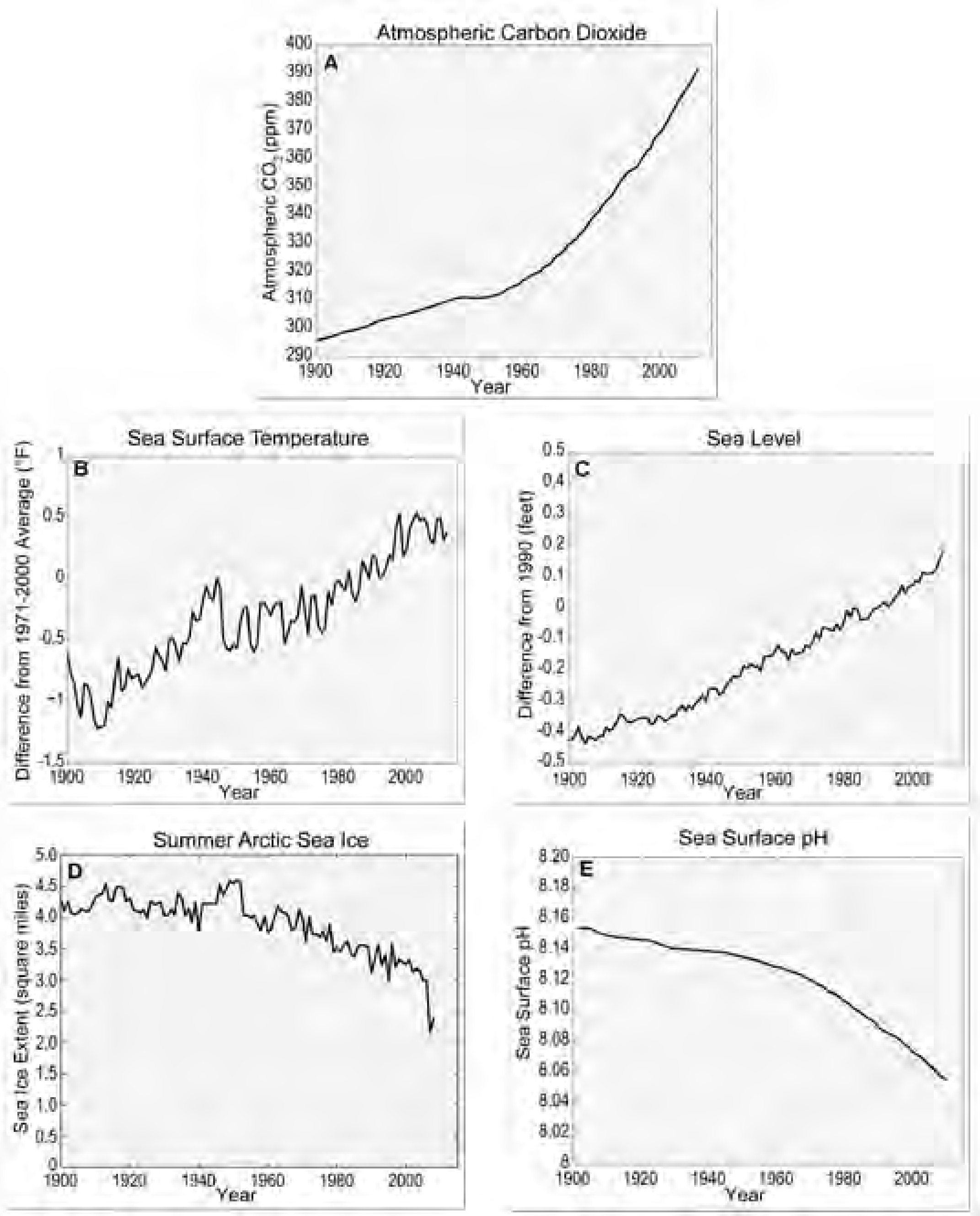


Figure 24.2. As heat-trapping gases, primarily *carbon dioxide (CO_2)* (panel A), have increased over the past decades, not only has air temperature increased worldwide, but so has the temperature of the ocean's surface (panel B). The increased ocean temperature, combined with melting of glaciers and ice sheets on land, is leading to higher sea levels (panel C). Increased air and ocean temperatures are also causing the continued, dramatic decline in Arctic sea ice during the summer (panel D). Additionally, the ocean is becoming more acidic as increased atmospheric CO_2 dissolves into it (panel E). (CO_2 data from Etheridge 2010,[20] Tans and Keeling 2012,[21] and NOAA NCDC 2012;[22] SST data from NOAA NCDC 2012[22] and Smith et al. 2008;[10] Sea level data from CSIRO 2012[23] and Church and White 2011;[19] Sea ice data from University of Illinois 2012;[24] pH data from Doney et al. 2012[4]).

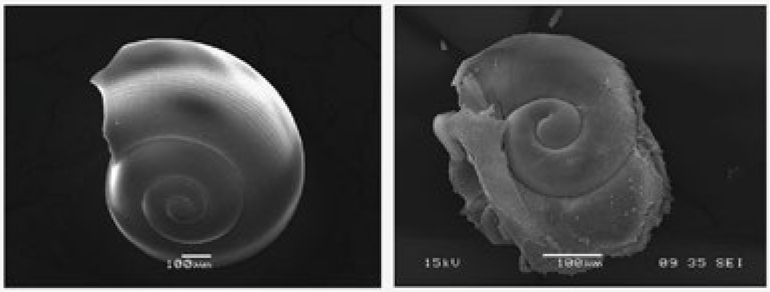
Key Message 2: Ocean Acidification Alters Marine Ecosystems

The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.

Atmospheric carbon dioxide (CO_2) has risen by about 40% above pre-industrial levels.[21,28] The ocean absorbs about a quarter of human-caused emissions of carbon dioxide annually, thereby changing seawater chemistry and decreasing pH (making seawater more acidic) (Ch. 2: Our Changing Climate, Key Message 12).[3,29] Surface ocean pH has declined by 0.1 units, equivalent to a 30% increase in ocean acidity, since pre-industrial times.[30] Ocean acidification will continue in the future due to the interaction of atmospheric carbon dioxide and ocean water. Regional differences in ocean pH occur as a result of variability in regional or local conditions, such as upwelling that brings subsurface waters up to the surface.[31] Locally, coastal waters and estuaries can also exhibit acidification as the result of pollution and excess nutrient inputs.

More acidic waters create repercussions along the marine food chain. For example, calcium carbonate is a skeletal component of a wide variety of organisms in the oceans, including corals. The chemical changes caused by the uptake of CO_2 make it more difficult for these living things to form and maintain calcium carbonate shells and skeletal components and increases erosion of coral reefs,[32] resulting in alterations in marine ecosystems that will become more severe as present-day trends in acidification continue or accelerate (Ch. 22: Alaska; Ch. 23: Hawai‘i and Pacific Islands).[33,34,35] Tropical corals are particularly susceptible to the combination of ocean acidification and ocean warming, which would threaten the rich and biologically diverse coral reef habitats.

Over 90% of seafood consumed in the U.S. is imported, and more than half of the imported seafood comes from aquaculture (fish and shellfish farming).[1] While only 1% of U.S. seafood comes from domestic shellfish farming, the industry is locally important. In addition, shellfish have historically been an important cultural and food resource for indigenous peoples along our coasts (Ch. 12: Indigenous Peoples, Key Message 1). Increased ocean acidification, low-oxygen events, and rising temperatures are already affecting shellfish aquaculture operations. Higher temperatures are predicted to increase aquaculture potential in poleward regions, but decrease it in the tropics.[37] Acidification, however, will likely reduce growth and survival of shellfish stocks in all regions.[34]



Pteropods, or “sea butterflies,” are eaten by a variety of marine species ranging from tiny krill to salmon to whales. The photos show what happens to a pteropod’s shell in seawater that is too acidic. On the left is a shell from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod in a region where the water is more acidic. (Photo credits: (left) Bednaršek et al. 2012;[105] (right) Nina Bednaršek).

Ocean Acidification Reduces Size of Clams

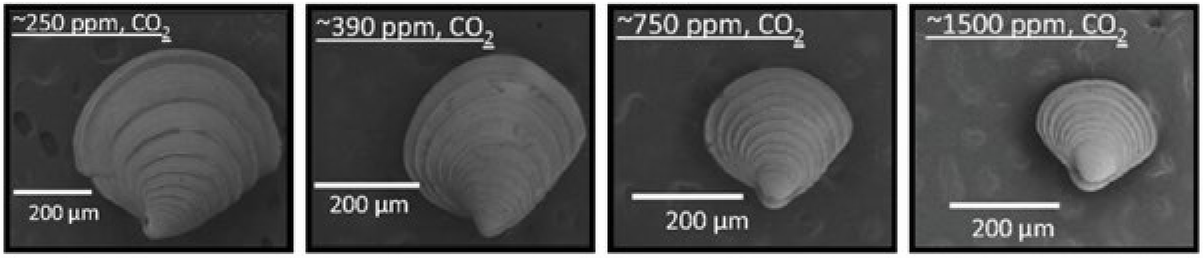


Figure 24.3. The 36-day-old clams in the photos are a single species, *Mercenaria mercenaria*, grown in the laboratory under varying levels of carbon dioxide (CO_2) in the air. CO_2 is absorbed from the air by ocean water, acidifying the water and thus reducing the ability of juvenile clams to grow their shells. As seen in the photos, where CO_2 levels rise progressively from left to right, 36-day-old clams (measured in microns) grown under elevated CO_2 levels are smaller than those grown under lower CO_2 levels. The highest CO_2 level, about 1500 parts per million (ppm; far right), is higher than most projections for the end of this century but could occur locally in some estuaries. (Figure source: Talmage and Gobler 2010[36]).

THE IMPACTS OF OCEAN ACIDIFICATION ON WEST COAST AQUACULTURE

Ocean acidification has already changed the way shellfish farmers on the West Coast conduct business. For oyster growers, the practical effect of the lowering pH of ocean water has not only been to make the water more acidic, but also more corrosive to young shellfish raised in aquaculture facilities. Growers at Whiskey Creek Hatchery, in Oregon's Netarts Bay, found that low pH seawater during spawning reduced growth in mid-stage larval (juvenile) Pacific oysters.[38] Hatcheries in Washington State have also experienced losses of spat (oyster larvae that have attached to a surface and begun to develop a shell) due to water quality issues that include other human-caused effects like dredging and pollution.[39] Facilities like the Taylor Shellfish Farms hatchery on Hood Canal have changed their production techniques to respond to increasing acidification in Puget Sound.

These impacts bring to light a potential challenge: existing natural variation may interact with human-caused changes to produce unanticipated results for shell-forming marine life, especially in coastal regions.[40] As a result, there is an increasing need for information about water chemistry conditions, such as data obtained through the use of sensor networks. In the case of Whiskey Creek, instruments installed in collaboration with ocean scientists created an "early warning" system that allows oyster growers to choose the time they take water into the hatchery from the coastal ocean. This allows them to avoid the lower-pH water related to upwelling and the commensurate loss of productivity in the hatchery.

From a biological perspective, these kinds of preventative measures can help produce higher-quality oysters. Studies on native Olympia oysters (*Ostrea lurida*) show that there is a "carry-over" effect of acidified water – oysters exposed to acidic conditions while in the juvenile stage continue to grow slower in later life stages.[41] Research on some oyster species such as Pacific oyster (*Crassostrea gigas*), the commercially important species in U.S. west coast aquaculture, shows that specially selected strains can be more resistant to acidification.[42]

Overall, economically important species such as oysters, mussels, and sea urchins are highly vulnerable to changes in ocean conditions brought on by climate change and rising atmospheric CO_2 levels. Sea temperature and acidification are expected to increase; the acidity of surface seawater is projected to nearly double by the end of this century. Some important cultured species may be influenced in larval and juvenile developing stages, during fertilization, and as adults,[43] resulting in lower productivity. Action groups, such as the California Current Acidification Network (C-CAN), are working to address the needs of the shellfish industry – both wild and aquaculture-based fisheries – in the face of ocean change. These efforts bring scientists from across disciplines together with aquaculturists, fishermen, the oceanographic community, and state and federal decision-makers to ensure a concerted, standardized, and cost-effective approach to gaining new understanding of the impact of acidification on ecosystems and the economy.[44]

Key Message 3: Habitat Loss Affects Marine Life

Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.

Species have responded to climate change in part by shifting where they live.[45] Such range shifts result in ecosystem changes, including the relationships between species and their connection to habitat, because different species respond to changing conditions in different ways. This means that ocean ecosystems are changing in complex ways, with accompanying changes in ecosystem functions (such as nutrient cycling, productivity of species, and predator-prey relationships). Overall habitat extent is expected to change as well, though the degree of range migration will depend upon the life history of particular species. For example, reductions in seasonal sea-ice cover and higher surface temperatures may open up new habitats in polar regions for some important fish species, such as cod, herring, and pollock.[46] However, the continuing presence of cold bottom-water temperatures on the Alaskan Continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea.[47] In addition, warming may cause reductions in the abundance of some species, such as pollock, in their current ranges in the Bering Sea.[48] For other ice-dependent species, including several marine mammals such as polar bears, walruses, and many seal species, the loss of their critically important habitat will result in population declines.[49] Additionally, climate extremes can facilitate biological invasions by a variety of mechanisms such as increased movement or transport of invasive species, and decreased resilience of native species, so that climate change could increase existing impacts from human transport.[50] These changes will result in changing interactions among species with consequences that are difficult to predict. Tropical species and ecosystems may encounter similar difficulties in migrating poleward as success of some key species such as corals may be limited by adequate bottom substrate, water clarity, and light availability.[51]

Climate change impacts such as increasing ocean temperatures can profoundly affect production of natural stocks of fish by changing growth, reproduction, survival, and other critical characteristics of fish stocks and ecosystems. For species that migrate to freshwater from the sea, like salmon, some published studies indicate earlier start of spawning migration, warming stream temperatures, and extirpation in southern extent of range, all of which can affect productivity.[4,52] To remain within their normal temperature range, some fish stocks are moving poleward and to deeper water.[53,54] Fishery productivity is predicted to decline in the lower 48 states, but increase in parts of Alaska.[55] However, projections based only on temperature may neglect important food web effects. Fishing costs are predicted to increase as fisheries transition to new species and as processing plants and fishing jobs shift poleward.[18] The cumulative impact of such changes will be highly variable on regional scales because of the combination of factors – some acting in opposite directions. Some areas will benefit from range expansions of valuable species or increases in productivity, while others will suffer as species move away from previously productive areas.

CORAL REEF ECOSYSTEM COLLAPSE

Recent research indicates that 75% of the world's coral reefs are threatened due to the interactive effects of climate change and local sources of stress, such as overfishing, nutrient pollution, and disease.[56,57] In Florida, all reefs are rated as threatened, with significant impacts on valuable ecosystem services they provide.[58] Caribbean coral cover has decreased 80% in less than three decades.[59] These declines have in turn led to a flattening of the three dimensional structure of coral reefs and hence a decrease in the capacity of coral reefs to provide shelter and other resources for other reef-dependent ocean life.[60]

The relationship between coral and zooxanthellae (algae vital for reef-building corals) is disrupted by higher than usual temperatures and results in a condition where the coral is still alive, but devoid of all its color (bleaching). Bleached corals can later die or become infected with disease.[61,62] Thus, high temperature events alone can kill large stretches of coral reef, although cold water and poor water quality can also cause localized bleaching and death. Evidence suggests that relatively pristine reefs, with fewer human impacts and with intact fish and associated invertebrate communities, are more resilient to coral bleaching and disease.[63]

Warming Seas Are a Double-blow to Corals

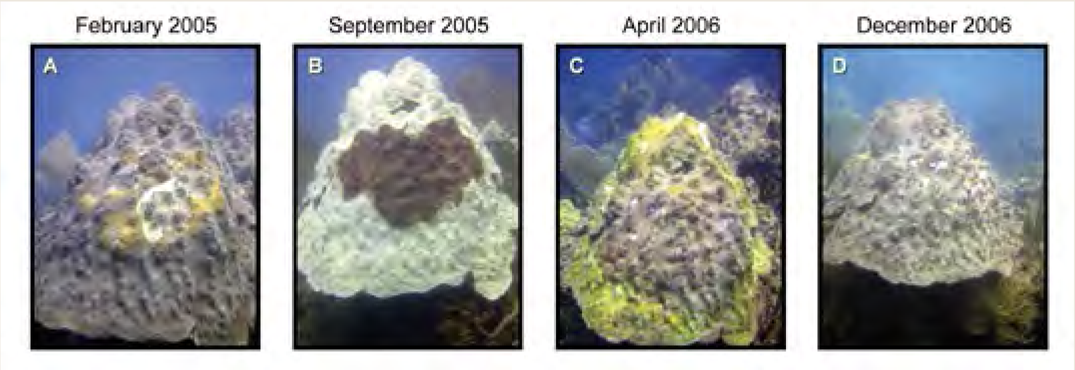


Figure 24.4. A colony of star coral (*Montastraea faveolata)* off the southwestern coast of Puerto Rico (estimated to be about 500 years old) exemplifies the effect of rising water temperatures. Increasing disease due to warming waters killed the central portion of the colony (yellow portion in A), followed by such high temperatures that bleaching - or loss of symbiotic algae from coral - occurred from the surrounding tissue (white area in B). The coral then experienced more disease in the bleached area on the periphery (C) that ultimately killed the colony (D). (Photo credit: Ernesto Weil).

Key Message 4: Rising Temperatures Linked to Diseases

Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and in marine life, including corals, abalones, oysters, fishes, and marine mammals.

There has been a significant increase in reported incidences of disease in corals, urchins, mollusks, marine mammals, turtles, and echinoderms (a group of some 70,000 marine species including sea stars, sea urchins, and sand dollars) over the last several decades.[64,65,66,67] Increasing disease outbreaks in the ocean affecting ecologically important species, which provide critically important habitat for other species such as corals,[65,68] algae,[69] and eelgrass,[70] have been linked with rising temperatures. Disease increases mortality and can reduce abundance for affected populations as well as fundamentally change ecosystems by changing habitat or species relationships. For example, loss of eelgrass beds due to disease can reduce critical nursery habitat for several species of commercially important fish.[70,71]

The complexity of the host/environment/pathogen interaction makes it challenging to separate climate warming from the myriad of other causes facilitating increased disease outbreaks in the ocean. However, three categories of disease-causing pathogens are unequivocally related to warming oceans. Firstly, warmer winters due to climate change can increase the overwinter survival and growth rates of pathogens.[67] A disease-causing parasite in oysters that proliferates at high water temperatures and high salinities spread northward up the eastern seaboard as water temperatures warmed during the 1990s.[72] Growth rates of coral disease lesions increased with winter and summer warming from 1996 to 2006.[62] Winter warming in the Arctic is resulting in increased incidence of a salmon disease in the Bering Sea and is now thought to be a cause of a 57% decline of Yukon Chinook salmon.[73]

Secondly, increasing disease outbreaks in ecologically important species like coral, eelgrass, and abalone have been linked with temperatures that are higher than the long-term averages. The spectacular biodiversity of tropical coral reefs is particularly vulnerable to warming because the corals that form the foundational reef structure live very near the upper temperature limit at which they thrive. The increasing frequency of record hot temperatures has caused widespread coral bleaching[66] and disease outbreaks[65] and is a principal factor contributing to the International Union for the Conservation of Nature listing a third of the reef-building corals as vulnerable, endangered, or critically endangered [74] and the National Oceanic and Atmospheric Administration proposing to list 66 species of corals under the Endangered Species Act.[75,76] In the Chesapeake Bay, eelgrass died out almost completely during the record-hot summers of 2005 and 2010,[77] and the California black abalone has been driven to the edge of extinction by a combination of warming water and bacterial disease.[78]

Thirdly, there is evidence that increased water temperature is responsible for the enhanced survival and growth of certain marine bacteria that make humans sick.[78] Increases in growth of *Vibrio parahaemolyticus* (a pathogenic bacterial species) during the warm season are responsible for human illnesses associated with oysters harvested from the Gulf of Mexico[79] and northern Europe.[80] *Vibrio vulnificus*, which is responsible for the overwhelming majority of reported seafood-related deaths in the United States,[81] is also a significant and growing source of potentially fatal wound infections associated with recreational swimming, fishing-related cuts, and seafood handling, and is most frequently found in water with a temperature above 68°F.[79,81,82]

Key Message 5: Economic Impacts of Marine-related Climate Change

Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.

Altered environmental conditions due to climate change will affect, in both positive and negative ways, human uses of the ocean, including transportation, resource use and extraction, leisure and tourism activities and industries, in the nearshore and offshore areas. Climate change will also affect maritime security and governance. Arctic-related national security concerns and threats to national sovereignty have also been a recent focus of attention for some researchers.[83,84] With sea ice receding in the Arctic as a result of rising temperatures, global shipping patterns are already changing and will continue to change considerably in the decades to come.[84,85] The increase in maritime traffic could make disputes over the legal status of sea lines-of-communication and international straits more pointed, but mechanisms exist to resolve these disputes peacefully through the Law of the Sea Convention and other customary international laws.

Resource use for fisheries, aquaculture, energy production, and other activities in ocean areas will also need to adjust to changing ocean climate conditions. In addition to the shift in habitat of living resources discussed above, changing ocean and weather conditions due to human-induced climate change make any activities at sea more difficult to plan, design, and operate.

In the United States, the healthy natural services (such as fishing and recreation) and cultural resources provided by the ocean also play a large economic role in our tourism industry. Nationally in 2010, 2.8% of gross domestic product, 7.52 million jobs, and $1.11 trillion in travel and recreational total sales are supported by tourism.[86] In 2009-2010, nine of the top ten states and U.S. territories and seven of the top ten cities visited by overseas travelers were coastal, including the Great Lakes. Changes in the location and distribution of marine resources (such as fish, healthy reefs, and marine mammals) due to climate change will affect the recreational industries and all the people that depend on reliable access to these resources in predictable locales. For example, as fish species shift poleward or to deeper waters,[54,87] these fish may be less accessible to recreational fishermen. Similar issues will also affect commercial fishing.

Similarly, new weather conditions differing from the historical pattern will pose a challenge for tourism, boating, recreational fishing, diving, and snorkeling, all of which rely on highly predictable, comfortable water and air temperatures and calm waters. For example, the strength of hurricanes and the number of strong (Category 4 and 5) hurricanes are projected to increase over the North Atlantic (Ch. 2: Our Changing Climate). Changes in wind patterns[88] and wave heights have been observed[89] and are projected to continue to change in the future.[90] This means that the public will not be able to rely on recent experience in planning leisure and tourism activities.[91,92] As weather patterns change and air and sea surface temperatures rise, preferred locations for recreation and tourism also may change. In addition, infrastructure such as marinas, marine supply stores, boardwalks, hotels, and restaurants that support leisure activities and tourism will be negatively affected by sea level rise. They may also be affected by increased storm intensity and changing wave heights,[92] as well as elevated storm surge due to sea level rise and other expected effects of a changing climate; these impacts will vary significantly by region.[93]

Key Message 6: Initiatives Serve as a Model

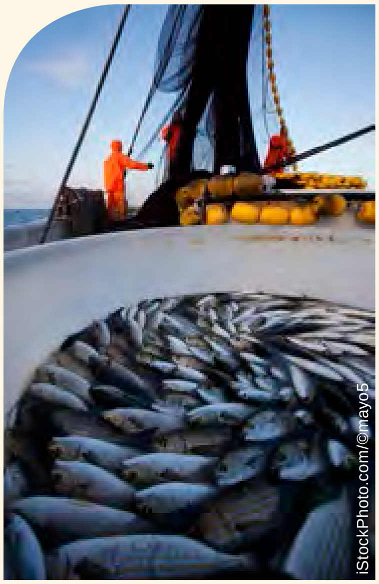
In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.

Climate considerations can be integrated into planning, restoration, design of marine protected areas, fisheries management, and aquaculture practices to enhance ocean resilience and adaptive capacity. Many existing sustainable-use strategies, such as ending overfishing, establishing protected areas, and conserving habitat, are known to increase resilience. Analyses of fishery management and climate scenarios suggest that adjustments to harvest regimes (especially reducing harvest rates of over-exploited species) can improve catch stability under changing climate conditions. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years.[94] The stability of international ocean and fisheries treaties, particularly those covering commercially exploited and critical species, might be threatened as the ocean changes.[95]

The fact that the climate is changing is beginning to be incorporated into existing management strategies. New five-year strategies for addressing flooding, shoreline erosion, and coastal storms have been developed by most coastal states under their Coastal Zone Management Act programs.[3] Many of these plans are explicitly taking into account future climate scenarios as part of their adaptation initiatives. The North Pacific Fishery Management Council and NOAA have declared a moratorium on most commercial fisheries in the U.S. Arctic pending sufficient understanding of the changing productivity of these fishing grounds as they become increasingly ice-free. Private shellfish aquaculture operations are changing their business plans to adapt to ocean acidification.[38,39] These changes include monitoring and altering the timing of spat settlement dependent on climate change induced conditions, as well as seeking alternative, acid-resistant strains for culturing. Marine protected areas in the National Marine Sanctuary (NMS) System are gradually preparing climate impact reports and climate adaptation action plans under their Climate Smart Sanctuary Initiative.[96]

Additionally, there is promise in restoring key habitats to provide a broad suite of benefits that can reduce climate impacts with relatively little ongoing maintenance costs (see Ch. 25: Coasts; Ch. 28: Adaptation). For example, if in addition to sea level rise, an oyster reef or mangrove restoration strategy also included fish habitat benefits for commercial and recreational uses and coastal protection services, the benefits to surrounding communities could multiply quickly. Coral-reef-based tourism can be more resilient to climate change impacts through protection and restoration, as well as reductions of pollution and other habitat-destroying activities. Developing alternative livelihood options as part of adaptation strategies for marine food-producing sectors can help reduce economic and social impacts of a changing climate.

CLIMATE IMPACTS ON NEW ENGLAND FISHERIES


iStockPhoto.com/©mayo5

Fishing in New England has been associated with bottom-dwelling fish for more than 400 years, and is a central part of the region's cultural identity and social fabric. Atlantic halibut, cod, haddock, flounders, hakes, pollock, plaice, and soles are included under the term "groundfish." The fishery is pursued by both small boats (less than 50 feet long) that are typically at sea for less than a day, and by large boats (longer than 50 feet) that fish for a day to a week at a time. These vessels use home ports in more than 100 coastal communities from Maine to New Jersey, and the landed value from fisheries in New England and the Mid-Atlantic in 2010 was nearly $1.2 billion.[76] Captains and crew are often second- or third-generation fishermen who have learned the trade from their families.

From 1982 to 2006, sea surface temperature in the coastal waters of the Northeast warmed by close to twice the global rate of warming over this period.[97] Long-term monitoring of bottom-dwelling fish communities in New England revealed that the abundance of warm-water species increased, while cool-water species decreased.[54,98] A recent study suggests that many species in this community have shifted their geographic distributions northward by up to 200 miles since 1968, though substantial variability among species also exists.[54] The northward shifts of these species are reflected in the fishery as well: landings and landed value of these species have shifted towards northern states such as Massachusetts and Maine, while southern states have seen declines (see Figure 24.5).

The economic and social impacts of these changes depend in large part on the response of the fishing communities in the region.[99] Communities have a range of strategies for coping with the inherent uncertainty and variability of fishing, including diversification among species and livelihoods, but climate change imposes both increased variability and sustained change that may push these fishermen beyond their ability to cope.[100] Larger fishing boats can follow the fish to a certain extent as they shift northward, while smaller inshore boats will be more likely to leave fishing or switch to new species.[100] Long-term viability of fisheries in the region may ultimately depend on a transition to new species that have shifted from regions farther south.[18]

Fisheries Shifting North

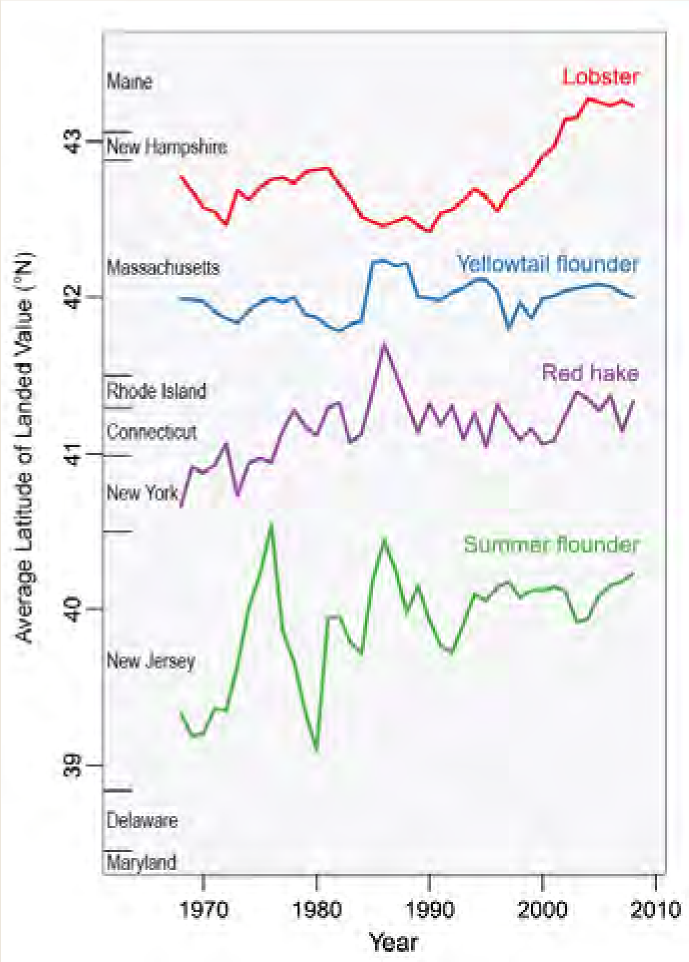


Figure 24.5. Ocean species are shifting northward along U.S. coastlines as ocean temperatures rise. As a result, over the past 40 years, more northern ports have gradually increased their landings of four marine species compared to the earlier pattern of landed value. While some species move northward out of an area, other species move in from the south. This kind of information can inform decisions about how to adapt to climate change. Such adaptations take time and have costs, as local knowledge and equipment are geared to the species that have long been present in an area. (Figure source: adapted from Pinsky and Fogerty 2012[101]).

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

A central component of the assessment process was the Oceans and Marine Resources Climate assessment workshop that was held January 23-24, 2012, at the National Oceanographic and Atmospheric Administration (NOAA) in Silver Spring, MD, and simultaneously, via web teleconference, at NOAA in Seattle, WA. In the workshop, nearly 30 participants took part in a series of scoping presentations and breakout sessions that began the process leading to a foundational Technical Input Report (TIR) entitled "Oceans and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment."[102] The report, consisting of nearly 220 pages of text organized into 7 sections with numerous subsections and more than 1200 references, was assembled by 122 authors representing governmental agencies, non-governmental organizations, tribes, and other entities.

The chapter author team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR[102] and of approximately 25 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The chapter author team met at Conservation International in Arlington, VA on 3-4 May 2012 for expert deliberation of draft key messages by the authors, wherein each message was defended before the entire author team before the key message was selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message to help define "key vulnerabilities."

KEY MESSAGE #1 TRACEABLE ACCOUNT

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Description of evidence base

The key message is supported by extensive evidence documented in Sections 2 and 3 of the Oceans Technical Input Report[102] and in the additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Relevant and recent peer-reviewed publications,[5,7,8] including many others that are cited therein, describe evidence that ocean temperature has risen over the past century. This evidence base includes direct and indirect temperature measurements, paleoclimate records, and modeling results.

There are also many relevant and recent peer-reviewed publications describing changes in physical and chemical ocean properties that are underway due to climate change.[11,14]

New information and remaining uncertainties

Important new information since the last National Climate Assessment[103] includes the latest update to a data set of ocean temperatures.[7]

There is accumulating new information on all of these points with regard to physical and chemical changes in the ocean and resultant impacts on marine ecosystems. Both measurements and model results are continuing to sharpen the picture.

A significant area of uncertainty remains with regard to the region-by-region impacts of warming, acidification, and associated changes in the oceans. Regional and local conditions mean that impacts will not be uniform around the U.S. coasts or internationally. Forecasting of regional changes is still an area of very active research, though the overall patterns for some features are now clear.

Large-scale and recurring climate phenomena (such as the El Niño Southern Oscillation, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation) cause dramatic changes in biological productivity and ecosystem structure and make it difficult to discern climate-driven trends.

Current time series of biological productivity are restricted to a handful of sites around the globe and to a few decades, and global, comprehensive satellite time series of ocean color are even shorter, beginning in 1997. Based on an analysis of different in situ datasets, one research group suggested a decline of 1% per year over the past century, but these findings may be an artifact of limited data and have been widely debated.[14,104] However, the few in situ time series mostly indicate increases in biological productivity over the past 20 years, but with clear links to regional changes in climate.[14]

Assessment of confidence based on evidence

Confidence that the ocean is warming and acidifying, and that sea level is rising is **very high**. Changes in other physical and chemical properties such as ocean circulation, wave heights, oxygen minimums, and salinity are of **medium** confidence. For ecosystem changes, there is **high** confidence that these are occurring and will persist and likely grow in the future, though the details of these changes are highly geographically variable.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Numerous references provide evidence for the increasing acidity (lower pH) of oceans around the world (Ch. 2: Our Changing Climate, Key Message 12).[3,31]

There is a rapid growth in peer-reviewed publications describing how ocean acidification will impact ecosystems,[33,34] but to date evidence is largely based on studies of calcification rather than growth, reproduction, and survival of organisms. For these latter effects, available evidence is from laboratory studies in low pH conditions, rather than in situ observations.[35]

New information and remaining uncertainties

The interplay of environmental stressors may result in “surprises” where the synergistic impacts may be more deleterious or more beneficial than expected. Such synergistic effects create complexities in predicting the outcome of the interplay of stressors on marine ecosystems. Many, but not all, calcifying species are affected by increased acidity in laboratory studies. How those responses will cascade through ecosystems and food webs is still uncertain. Although studies are underway to expand understanding of ocean acidification on all aspects of organismal physiology, much remains to be learned.

Assessment of confidence based on evidence

Confidence is **very high** that carbon dioxide emissions to the atmosphere are causing ocean acidification, and **high** that this will alter marine ecosystems. The nature of those alterations is unclear, however, and predictions of most specific ecosystem changes have **low** confidence at present, but with **medium** confidence for coral reefs.

Key message #3 Traceable Account

Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Many peer-reviewed publications[56,70] describe threats to coral reefs induced by global change.

There are also many relevant and recent peer-reviewed publications[53,54,87] that discuss impacts on marine species and resources of habitat change that is induced by climate change.

New information and remaining uncertainties

Regional and local variation is, again, a major component of the remaining uncertainties. Different areas, habitats, and species are responding differently and have very different adaptive capacities. Those species that are motile will certainly respond differently, or at least at a different rate, by changing distribution and migration patterns, compared to species that do not move, such as corals.

Although it is clear that some fish stocks are moving poleward and to deeper water, how far they will move and whether most species will move remains unclear. A key uncertainty is the extent to which various areas will benefit from range expansions of valuable species or increases in productivity, while other areas will suffer as species move away from previously productive areas. The loss of critically important habitat due to climate change will result in changes in species interactions that are difficult to predict.

Assessment of confidence based on evidence

There is **very high** confidence that habitat and ecosystems are changing due to climate change, but that change is not unidirectional by any means. Distribution, abundance, and productivity changes are species and location dependent and may be increasing or decreasing in a complex pattern.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and in marine life, including corals, abalones, oysters, fishes, and marine mammals.

Description of evidence base

The key message is supported by extensive evidence in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

As noted in the chapter, the references document increased levels and ranges of disease coincident with rising temperatures.[64,65,66,67]

New information and remaining uncertainties

The interactions among host, environment, and pathogen are complex, which makes it challenging to separate warming due to climate change from other causes of disease outbreaks in the ocean.

Assessment of confidence based on evidence

There is **high** confidence that disease outbreaks and levels are increasing, and that this increase is linked to increasing temperatures. Again, there is substantial local to regional variation but the overall pattern seems consistent.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Many peer-reviewed publications describe the predicted impacts of climate change on tourism and recreation industries and their associated infrastructure.[91,92]

New information and remaining uncertainties

Given the complexity of transportation, resource use and extraction, and leisure and tourism activities, there are large uncertainties in impacts in specific locales or for individual activities. Some businesses and communities may be able to adapt rapidly, others less so. Infrastructure impacts of climate change will also be an important part of the ability of businesses, communities, and the public to adapt.

Assessment of confidence based on evidence

As with many other impacts of climate change, the evidence that change is occurring is very strong but the resultant impacts are still uncertain. For all of these human uses, and the associated costs and disruption, the evidence is suggestive and confidence **medium** on the effects of the ongoing changes in ocean conditions.

KEY MESSAGE #6 TRACEABLE ACCOUNT

In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Scenarios suggest that adjustments to fish harvest regimes can improve catch stability under increased climate variability. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years.[94]

New information and remaining uncertainties

Efforts are underway to enhance the development and deployment of science in support of adaptation, to improve understanding and awareness of climate-related risks, and to enhance analytic capacity to translate understanding into planning and management activities. While critical knowledge gaps exist, there is a wealth of climate- and ocean-related science pertinent to adaptation.102

Assessment of confidence based on evidence

There is **high** confidence that adaptation planning will help mitigate the impacts of changing ocean conditions. But there is much work to be done to craft local solutions to the set of emerging issues in ocean and coastal areas.

Climate Change Impacts in the United States

CHAPTER 25
COASTAL ZONE DEVELOPMENT AND ECOSYSTEMS

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On the Web: http://nca2014.globalchange.gov/report/regions/coasts

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

25 COASTAL ZONE

DEVELOPMENT AND ECOSYSTEMS

KEY MESSAGES

1. **Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, erosion, and other climate-related changes.**

2. **Nationally important assets, such as ports, tourism and fishing sites, in already-vulnerable coastal locations, are increasingly exposed to sea level rise and related hazards. This threatens to disrupt economic activity within coastal areas and the regions they serve and results in significant costs from protecting or moving these assets.**

3. **Socioeconomic disparities create uneven exposures and sensitivities to growing coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable people from coastal areas.**

4. **Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.**

5. **Leaders and residents of coastal regions are increasingly aware of the high vulnerability of coasts to climate change and are developing plans to prepare for potential impacts on citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.**

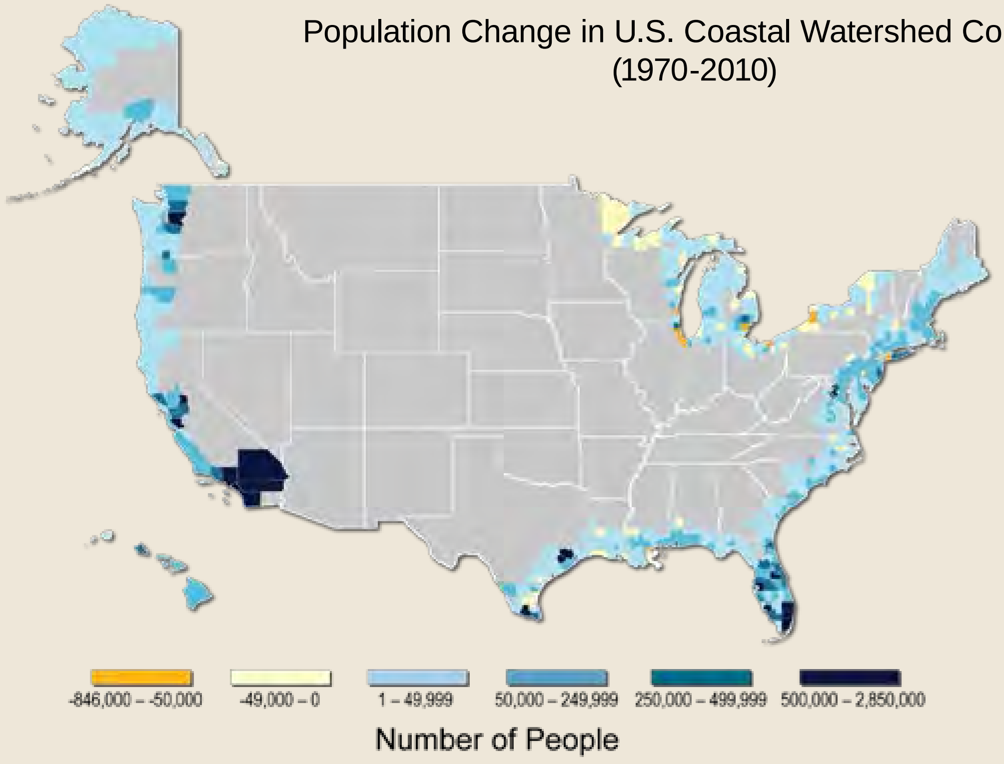

Figure 25.1. U.S. population growth in coastal watershed counties has been most significant over the past 40 years in urban centers such as Puget Sound, San Francisco Bay, southern California, Houston, South Florida and the northeast metropolitan corridor. A coastal watershed county is defined as one where either 1) at a minimum, 15% of the county's total land area is located within a coastal watershed, or 2) a portion of or an entire county accounts for at least 15% of a coastal USGS 8-digit cataloging unit.[1] Residents in these coastal areas can be considered "the U.S. population that most directly affects the coast."[1] We use this definition of "coastal" throughout the chapter unless otherwise specified. (Data from U.S. Census Bureau).

Each year, more than 1.2 million people move to the coast, collectively adding the equivalent of nearly one San Diego, or more than three Miami's, to the Great Lakes or open-ocean coastal watershed counties and parishes of the United States. As a result, 164 million Americans – more than 50% of the population – now live in these mostly densely populated areas[1,2] (Figure 25.1) and help generate 58% of the national gross domestic product (GDP).[3] People come – and stay – for the diverse and growing employment opportunities in recreation and tourism, commerce, energy and mineral production, vibrant urban centers, and the irresistible beauty of our coasts.[4] Residents, combined with the more than 180 million tourists that flock to the coasts each year,[5,6] place heavy demands on the unique natural systems and resources that make coastal areas so attractive and productive.[7]

Meanwhile, public agencies and officials are charged with balancing the needs of economic vitality and public safety, while sustaining the built and natural environments in the face of risks from well-known natural hazards such as storms, flooding, and erosion.[8] Although these risks play out in different ways along the United States' more than 94,000 miles of coastline,[9] all coasts share one simple fact: no other region concentrates so many people and so much economic activity on so little land, while also being so relentlessly affected by the sometimes violent interactions of land, sea, and air.

Humans have heavily altered the coastal environment through development, changes in land use, and overexploitation of resources. Now, the changing climate is imposing additional stresses,[10] making life on the coast more challenging (Figure 25.2). The consequences will ripple through the entire nation, which depends on the productivity and vitality of coastal regions.

COASTAL RESILIENCE DEFINED

Resilience means different things to different disciplines and fields of practice. In this chapter, resilience generally refers to an ecological, human, or physical system's ability to persist in the face of disturbance or change and continue to perform certain functions.[11] Natural or physical systems do so through absorbing shocks, reorganizing after disturbance, and adapting;[12] social systems can also consciously learn.[13]

Events like Superstorm Sandy in 2012 have illustrated that public safety and human well-being become jeopardized by the disruption of crucial lifelines, such as water, energy, and evacuation routes. As climate continues to change, repeated disruption of lives, infrastructure functions, and nationally and internationally important economic activities will pose intolerable burdens on people who are already most vulnerable and aggravate existing impacts on valuable and irreplaceable natural systems. Planning long-term for these changes, while balancing different and often competing demands, are vexing challenges for decision-makers (Ch. 26: Decision Support).

Flooding During High Tides

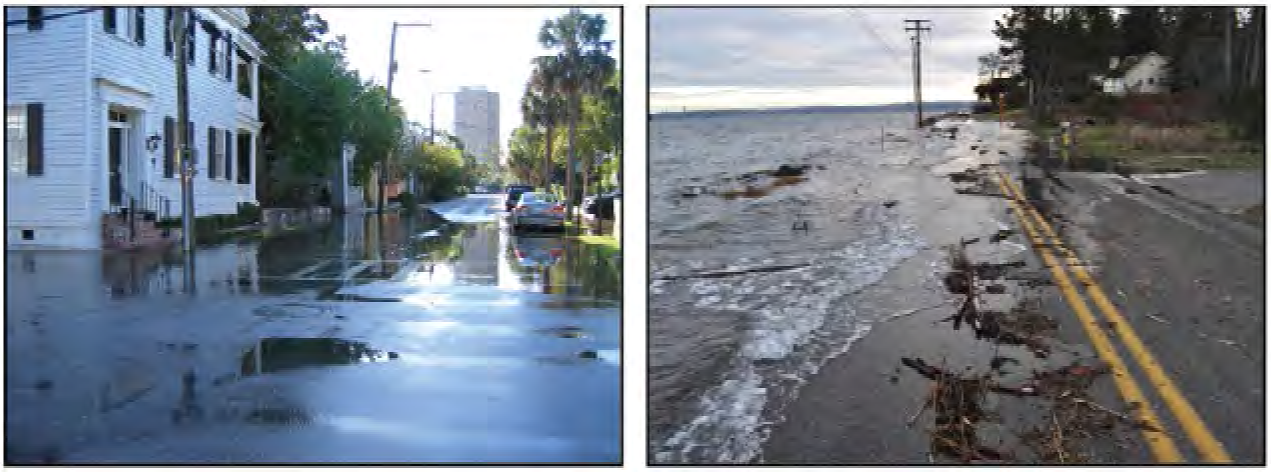

Figure 25.2. Sea level rise is not just a problem of the future, but is already affecting coastal communities such as Charleston, South Carolina, and Olympia in South Puget Sound through flooding during high tides. (Photo credits: (left) NOAA Coastal Services Center; (right) Ray Garrido, January 6, 2010, reprinted with permission by the Washington Department of Ecology).

Climate-related Drivers of Coastal Change

The primary climatic forces affecting the coasts are changes in temperature, sea and water levels, precipitation, storminess, ocean acidity, and ocean circulation.[7]

- Sea surface temperatures are rising[14] and are expected to rise faster over the next few decades,[15] with significant regional variation, and with the possibility for more intense hurricanes as oceans warm (Ch. 2: Our Changing Climate).

- Global average sea level is rising and has been doing so for more than 100 years (Ch.2: Our Changing Climate), and greater rates of sea level rise are expected in the future.[16] Higher sea levels cause more coastal erosion, changes in sediment transport and tidal flows, more frequent flooding from higher storm surges, landward migration of barrier shorelines, fragmentation of islands, and saltwater intrusion into aquifers and estuaries.[7,17,18,19]

- Rates of sea level rise are not uniform along U.S. coasts[20,21] and can be exacerbated locally by land subsidence or reduced by uplift.[22,23] Along the shorelines of the Great Lakes, lake level changes are uncertain (Ch. 18: Midwest), but erosion and sediment migration will be exacerbated by increased lakeside storm events, tributary flooding, and increased wave action due to loss of ice cover.[24]

- Patterns of precipitation change are affecting coastal areas in complex ways (Ch. 2: Our Changing Climate). In regions where precipitation increases, coastal areas will see heavier runoff from inland areas, with the already observed trend toward more intense rainfall events continuing to increase the risk of extreme runoff and flooding. Where precipitation is expected to decline and droughts to increase, freshwater inflows to the coast will be reduced (Ch. 3: Water).

- There has been an overall increase in storm activity near the Northeast and Northwest coastlines since about 1980.[25] Winter storms have increased slightly in frequency and intensity and their storm tracks have shifted northward.[26] The most intense tropical storms have increased in intensity in the last few decades.[27] Future projections suggest increases in hurricane rainfall and intensity (with a greater number of the strongest – Category 4 and 5 – hurricanes), a slight decrease in the frequency of tropical cyclones, and possible shifts in storm tracks, though the details remain uncertain (Ch. 2: Our Changing Climate).

- Marine ecosystems are being threatened by climate change and ocean acidification. The oceans are absorbing more carbon dioxide as the concentration in the atmosphere increases, resulting in ocean acidification, which threatens coral reefs and shellfish.[28,29,30] Coastal fisheries are also affected by rising water temperatures[31] and climate-related changes in oceanic circulation (Ch. 24: Oceans).[32,33] Wetlands and other coastal habitats are threatened by sea level rise, especially in areas of limited sediment supply or where barriers prevent onshore migration.[34] The combined effects of saltwater intrusion, reduced precipitation, and increased evapotranspiration will elevate soil salinities and lead to an increase in salt-tolerant vegetation[35,36] and the dieback of coastal swamp forests.[37]

None of these changes operate in isolation. The combined effects of climate changes with other human-induced stresses makes predicting the effects of climate change on coastal systems challenging. However, it is certain that these factors will create increasing hazards to the coasts' densely populated areas.[38,39,40]

Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC

Projected Sea Level Rise and Flooding by 2050

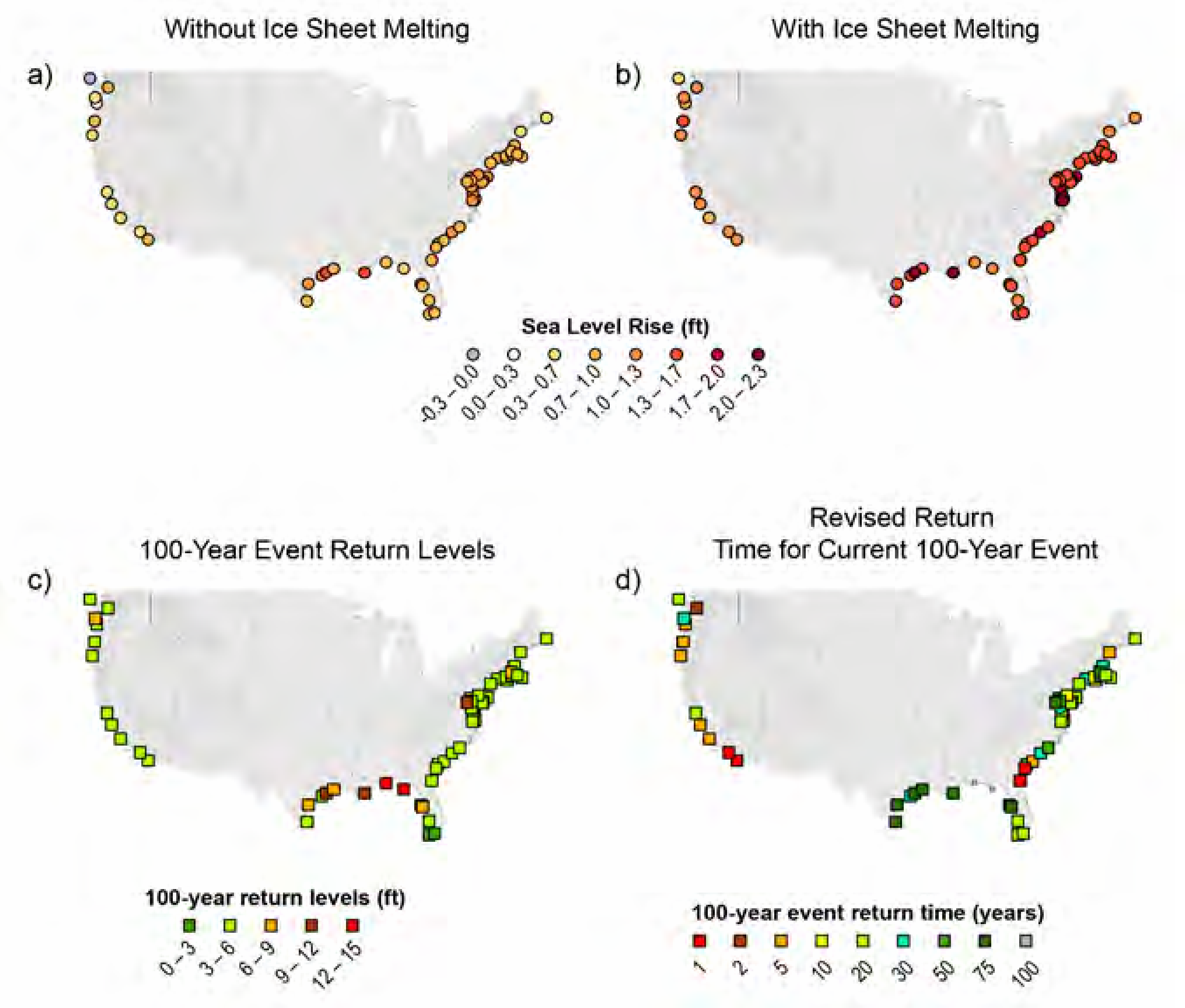

Figure 25.3. The amount of sea level rise (SLR) by 2050 will vary along different stretches of the U.S. coastline and under different SLR scenarios, mostly due to land subsidence or uplift (Ch.2: Our Changing Climate).[16] The panels show feet of sea level above 1992 levels at different tide gauge stations based on a) an 8 inch SLR and b) a 1.24 foot SLR by 2050. The flood level that has a 1% chance of occurring in any given year ("return level") is similarly projected to differ by region as a result of varying storm surge risk. Panel c) shows return levels for a 1.05 foot SLR above mean high tide by 2050. Finally, panel d) shows how a 1.05 foot SLR by 2050 could cause the level of flooding that occurs during today's 100-year storm to occur more frequently by mid-century, in some regions as often as once a decade or even annually. (Figure source: replicated Tebaldi et al. 2012[23] analysis with NCA sea level rise scenarios[16] for panels a) and b); data/ensemble SLR projections used for panels c) and d) from Tebaldi et al. 2012[23]; all estimates include the effect of land subsidence).

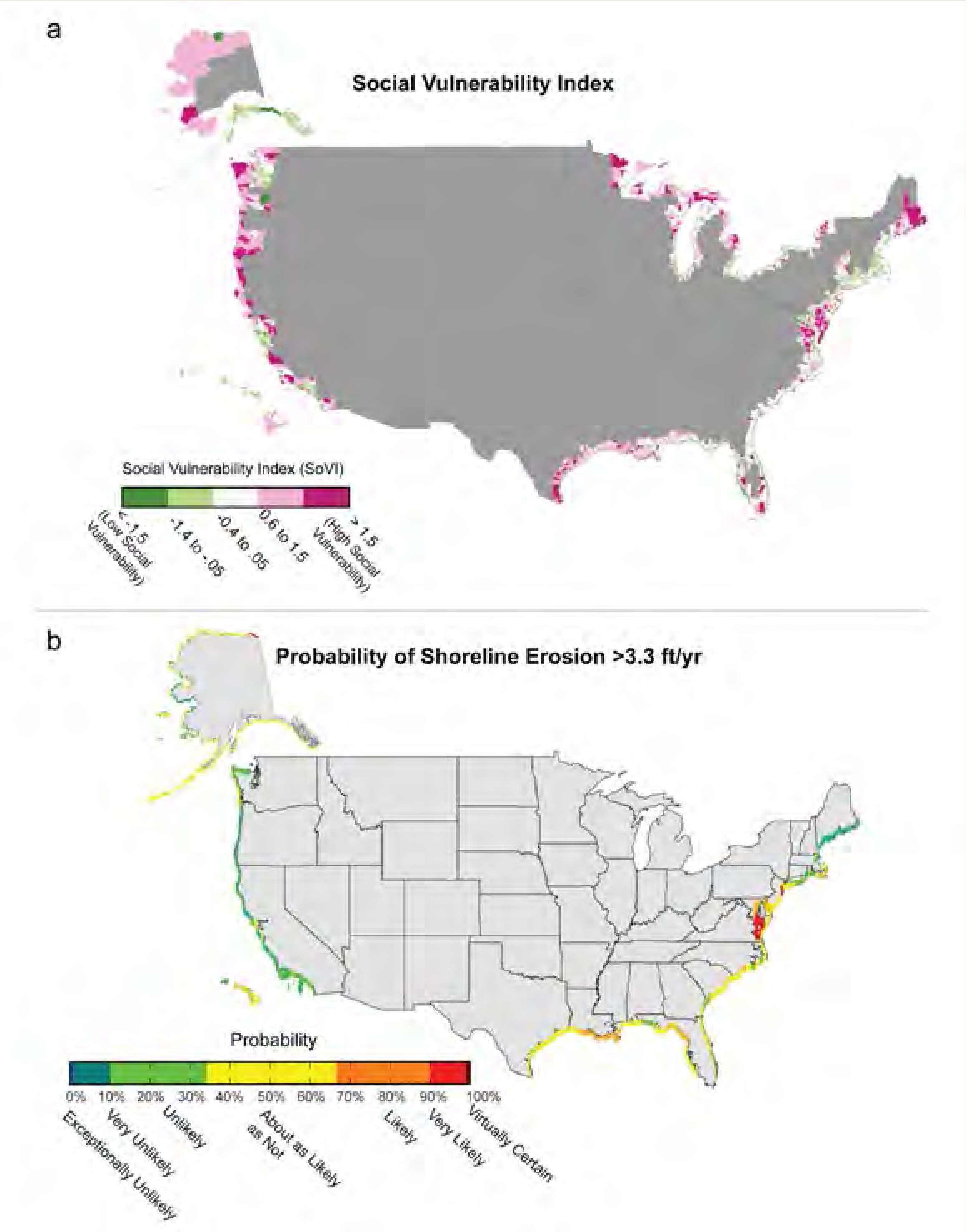

Figure 25.4. (a) Social Vulnerability, (b) Probability of Shoreline Erosion

(a) Social Vulnerabilty Index (SoVI) at the Census tract level for counties along the coast. The Social Vulnerability Index provides a quantitative, integrative measure for comparing the degree of vulnerability of human populations across the nation. A high SoVI (dark pink) typically indicates some combination of high exposure and high sensitivity to the effects of climate change and low capacity to deal with them. Specific index components and weighting are unique to each region (North Atlantic, South Atlantic, Gulf, Pacific, Great Lakes, Alaska, and Hawai'i). All index components are constructed from readily available Census data and include measures of poverty, age, family structure, location (rural versus urban), foreign-born status, wealth, gender, Native American status, and occupation.[41,42]

(b) Probability of Shoreline Erosion greater than 3.3 feet per year for counties along the coast. Probability is based on historical conditions only and does not reflect the possibility of acceleration due to increasing rates of sea level rise.[43]

Regional Differences in Climate Change Threats

PACIFIC NORTHWEST

- The substantial global sea level rise is regionally moderated by the continuing uplift of land, with few exceptions, such as the Seattle area and central Oregon.
- Commercial shellfish populations are at risk from ocean acidification.
- The region's relatively high economic dependence on commercial fisheries makes it sensitive to climate change impacts on marine species and ecosystems and related coastal ecosystems.
- Coastal storm surges are expected to be higher due to increases in sea level alone, and more intense-persistent storm tracks (atmospheric river systems) will increase coastal flooding risks from inland runoff.

GREAT LAKES

- Higher temperatures and longer growing seasons in the Great Lakes region favor production of blue-green and toxic algae that can harm fish, water quality, habitat, and aesthetics.
- Increased winter air temperatures will lead to decreased Great Lakes ice cover, making shorelines more susceptible to erosion and flooding.
- Current projections of lake level changes are uncertain.

NORTHEAST

- Highly built-up coastal corridor concentrates population and supporting infrastructure.
- Storm surges from nor'easters and hurricanes can cause significant damage.
- The historical rate of relative sea level rise varies across the region.
- Wetlands and estuaries are vulnerable to inundation from sea level rise; buildings and infrastructure are most vulnerable to higher storm surges as sea level rises.

CALIFORNIA

- Sea level has risen approximately 7 inches from 1900 to 2005, and is expected to rise at growing rates in this century.
- Higher temperatures; changes in precipitation, runoff and water supplies; and saltwater intrusion into coastal aquifers will result in negative impacts on coastal water resources.
- Coastal storm surges are expected to be higher due to increases in sea level alone, and more intense persistent storm tracks (atmospheric river systems) will increase coastal flooding risks from inland runoff.
- Expensive coastal development, critical infrastructure, and valuable coastal wetlands are at growing risk from coastal erosion, temporary flooding, and permanent inundation.
- The San Francisco Bay and San Joaquin/Sacramento River Delta are particularly vulnerable to sea level rise and changes in salinity, temperature, and runoff, endangering one of the ecological "jewels" of the West Coast, growing development, and crucial water infrastructure.

MID-ATLANTIC

- Rates of local sea level rise in the Chesapeake Bay are greater than the global average.
- Sea level rise and related flooding and erosion threaten coastal homes, infrastructure, and commercial development, including ports.
- Chesapeake Bay ecosystems are already heavily degraded, making them more vulnerable to climate-related impacts.

GULF COAST

- Hurricanes, land subsidence, sea level rise, and erosion already pose great risks to Gulf Coast areas, placing homes, critical infrastructure, and people at risk, and causing permanent land loss.
- Coastal inland and water temperatures are expected to rise; coastal inland areas are expected to become drier.
- There is still uncertainty about future frequency and intensity of Gulf of Mexico hurricanes but sea level rise will increase storm surges.
- The Florida Keys, South Florida, and coastal Louisiana are particularly vulnerable to additional sea level rise and saltwater intrusion.

HAWAI'I & PACIFIC ISLANDS

- Warmer and drier conditions will reduce freshwater supplies on many Pacific islands, especially on low lying islands and atolls.
- Sea level rise will continue at accelerating rates, exacerbating coastal erosion, damaging infrastructure and agriculture, reducing critical habitat, and threatening shallow coral reef systems.
- Extreme water levels occur when high tides combine with interannual and interdecadal sea level variations (such as ENSO, PDO, mesoscale eddy events) and storm surge.
- Coral reef changes pose threats to communities, cultures, and ecosystems.

ALASKA

- Summer sea ice is receding rapidly, altering marine ecosystems, allowing for greater ship access and offshore development, and making Native communities highly susceptible to coastal erosion.
- Ice loss from melting Alaskan and Canadian glaciers currently contributes almost as much to sea level rise as does melting of the Greenland Ice Sheet.
- Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries.

SOUTHEAST / CARIBBEAN

- A large number of cities, critical infrastructure, and water supplies are at low elevations and exposed to sea level rise, in some places moderated by land uplift.
- Ecosystems of the Southeast are vulnerable to loss from relative sea level rise, especially tidal marshes and swamps.
- Sea level rise will affect coastal agriculture through higher storm surges, saltwater intrusion, and impacts on freshwater supplies.
- The number of land-falling tropical storms may decline, reducing important rainfall.
- The incidence of harmful algal blooms is expected to increase with climate change, as are health problems previously uncommon in the region.

Figure 25.4. (c) Climate-Related Threats

(c) Regional Threats from Climate Change are compiled from technical input reports, the regional chapters in this report, and from scientific literature. For related information, see http://data.globalchange.gov/report/regional-differences-2012

ALASKA

- Newtok, AK, is relocating away from the eroding shoreline.

NORTHEAST

- Portland, ME, is assessing costs for retrofitting its wastewater infrastructure.
- New Hampshire's Coastal Adaptation Workgroup is providing education, guidance, and networking for local planners.
- City of Boston considers adaptation and mitigation equal priorities, and sea level rise is a top concern.
- Connecticut State Assembly amended the state's Coastal Management Act to promote adaptation to sea level rise.

GREAT LAKES

- Wisconsin's state adaptation plan includes emphasis on lake shorefront areas.
- Bay-Lake Regional Planning Commission updated hazard mitigation plans.
- Ohio's Lake Erie Commission is in the process of developing model shoreline development legislation.

PACIFIC NORTHWEST

- Swinomish Tribe's Climate Change Initiative highlights special challenges of coastal tribes.
- Oregon Sea Grant surveyed its coastal professionals on preparedness for local climate change impacts.

MID-ATLANTIC

- Delaware launched a multi-faceted effort to prepare coastal communities for sea level rise.
- Maryland's Comprehensive Strategy for Reducing Vulnerability to Climate Change has a strong initial focus on sea level rise and coastal hazards.
- The Hampton Roads area, including the City of Norfolk, Virgina, is working to reduce recurrent flooding and impacts on coastal infrastructrure.

CALIFORNIA

- San Diego Bay engaged in a multi-sector, multi-level stakeholder process to develop a first adaptation plan.
- California Ocean Protection Council developed sea level rise guidance for state and local governments.
- Bay Conservation and Development Commission passed Bay Plan Amendment.

GULF COAST

- Mississippi – Coastal Improvements Program includes buy-outs and relocation.
- 2012 Lousiana Coastal Master Plan ambitiously aims to protect and restore low-lying land.
- Entergy, America's Wetland Foundation, and Oxfam champion joint adaptation planning for America's Energy Coast.
- Texas requires rolling easements.

SOUTHEAST / CARIBBEAN

- NC Department of Transportation is raising the road bed of US Highway 64 to account for future sea level rise.
- The City of Charleston upgraded stormwater pumps and sewer systems to reduce tidal flooding.
- Charlotte Harbor National Estuary Program and City of Punta Gorda, FL, involved community stakeholders in its adaptation planning process.
- Southeast Florida Regional Climate Change Compact designated Adaptation Action Areas.

HAWAI'I & PACIFIC ISLANDS

- Researchers map sea level rise in Honolulu to help communities assess risks.
- USGS helps monitor saltwater intrusion on Majuro Atoll, Marshall Islands.

Figure 25.4. (d) Adaptation Activities

(d) Examples of Adaptation Activities in Coastal Areas of the U.S. and Affiliated Island States are compiled from technical input reports, the regional chapters in this report, and scientific literature. For related information, see http://data.globalchange.gov/report/coastal-adaptation-examples-2012

Key Message 1: Coastal Lifelines at Risk

Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, erosion, and other climate-related changes.

Key coastal vulnerabilities arise from complex interactions among climate change and other physical, human, and ecological factors. These vulnerabilities have the potential to fundamentally alter life at the coast and disrupt coast-dependent economic activities.

Coastal infrastructure is exposed to climate change impacts from both the landward and ocean sides.[44,45,46,47,48] Some unique characteristics increase the vulnerability of coastal infrastructure to climate change (Ch. 11: Urban).[7,49] For instance, many coastal regions were settled long ago, making much of the infrastructure older than in other locations.[50] Also, inflexibility of some coastal, water-dependent infrastructure, such as onshore gas and oil facilities, port facilities, thermal power plants, and some bridges, makes landward relocation difficult (Figure 25.5), and build-up of urban and industrial areas inland from the shoreline can inhibit landward relocation.[7]

Adapting Coastal Infrastructure to Sea Level Rise and Land Loss

Figure 25.5. This “mock-up” shows the existing Highway LA-1 and Leeville Bridge in coastal Louisiana (on the right) with a planned new, elevated bridge that would retain functionality under future, higher sea level conditions (center left). (Current sea level and sinking bridge are shown here.) A 7-mile portion of the planned bridge has been completed and opened to traffic in December 2011. (Figure source: Greater Lafourche Port Commission, reprinted with permission).

Infrastructure is built to certain site-specific design standards (such as the once-in-10-year, 24-hour rainstorm or the once-in-100-year flood) that take account of historical variability in climate, coastal, and hydrologic conditions. Impacts exceeding these standards can shorten the expected lifetime, increase maintenance costs, and decrease services. In general, higher sea levels, especially when combined with inland changes from flooding and erosion, will result in accelerated infrastructure impairment, with associated indirect effects on regional economies and a need for infrastructure upgrades, redesign, or relocation.[7,44,45,46,51]

The more than 60,000 miles of coastal roads[52] are essential for human activities in coastal areas (Ch. 5: Transportation), especially in case of evacuations during coastal emergencies.[53,54] Population growth to date and expected additional growth place increasing demands on these roads, and climate change will decrease their functionality unless adaptation measures are taken.[55,56] Already, many coastal roads are affected during storm events[57] and extreme high tides.[58] Moreover, as coastal bridges, tunnels, and roads are built or redesigned, engineers must account for inland and coastal changes, including drainage flooding, thawing permafrost, higher groundwater levels, erosion, and increasing saturation of roadway bases.[59] During Hurricane Katrina, many bridges failed because they had only been designed for river flooding but were also unexpectedly exposed to storm surges.[55,60]

Wastewater management and drainage systems constitute critical infrastructure for coastal businesses and residents (Ch. 3: Water). Wastewater treatment plants are typically located at low elevations to take advantage of gravity-fed sewage collection. Increased inland and coastal flooding make such plants more vulnerable to disruption, while increased inflows will reduce treatment efficiency.[47,61,62] Drainage systems – designed using mid-1900s rainfall records – will become overwhelmed in the future with increased rainfall intensity over more impervious surfaces, such as asphalt and concrete.[27,63,64,65] Sea level rise will increase pumping requirements for coastal wastewater treatment plants, reduce outlet capacities for drainage systems, and increasingly infiltrate sewer lines, while salt water intrusion into coastal aquifers will affect coastal water supplies and salt fronts will advance farther up into coastal rivers, affecting water supply intakes (Ch. 3: Water).[19,66] Together, these impacts increase the risks of urban flooding, combined sewer overflows, deteriorating coastal water quality, and human health impacts (Ch. 11: Urban; Ch. 9: Human Health).[67,68,69]

Coastal water infrastructure adaptation options include (but are not limited to):

- integrating both natural landscape features and human-engineered, built infrastructure to reduce stormwater runoff and wave attack, including, where feasible, creative use of dredge material from nearby coastal locations in the build-up of wetlands and berms (Figure 25.6);
- constructing seawalls around wastewater treatment plants and pump stations;
- pumping effluent to higher elevations to keep up with sea level rise;
- pumping freshwater into coastal aquifers to reduce infiltration of saltwater; and
- reusing water after treatment to replace diminished water supplies due to sea level rise.[70]

Technical and financial feasibility may limit how well and how long coastal infrastructure can be protected in place before it needs to be moved or abandoned. One group estimated that nationwide adaptation costs to utilities for wastewater systems alone could range between $123 billion and $252 billion by 2050 and, while not specific to coastal systems, gives a sense of the magnitude of necessary expenditures to avert climate change impacts.[71]

Ecosystem Restoration

Figure 25.6. A coastal ecosystem restoration project in New York City integrates revegetation (a form of green infrastructure) with bulkheads and riprap (gray or built infrastructure). Investments in coastal ecosystem conservation and restoration can protect coastal waterfronts and infrastructure, while providing additional benefits, such as habitat for commercial and recreational fish, birds, and other animal and plant species, that are not offered by built infrastructure. (Photo credit: Department of City Planning, New York City, reprinted with permission).

The nation's energy infrastructure, such as power plants, oil and gas refineries, storage tanks, transformers, and electricity transmission lines, are often located directly in the coastal floodplain.[48,72] Roughly two-thirds of imported oil enters the U.S. through Gulf of Mexico ports,[55] where it is refined and then transported inland. Unless adaptive measures are taken, storm-related flooding, erosion, and permanent inundation from sea level rise will disrupt these refineries (and related underground infrastructure) and, in turn, will constrain the supply of refined products to the rest of the nation (Ch. 4: Energy; Ch. 10: Energy, Water, and Land) (Figure 25.5).[73]

Coastal communities have a variety of options to protect, replace, and redesign existing infrastructure, including flood proofing and flood protection through dikes, berms, pumps, integration of natural landscape features, elevation, more frequent upgrades, or relocation.[74] Relocation of large coastal infrastructure away from the coastline can be very expensive and, for some facilities such as port installations, impossible due to the need for direct access to the shoreline. In most instances, the addition of new flood-proofed infrastructure in high-hazard zones has been viewed as a more cost-effective near-term option than relocation.[75] In these cases, significantly higher removal costs may be incurred later when sea level is higher or if the facility needs to be abandoned altogether in the future. This suggests that adaptation options are best assessed in a site-specific context, comprehensively weighing social, economic, and ecological considerations over multiple timeframes. A combination of gray and green infrastructure is increasingly recognized as a potentially cost-effective approach[67,76] to reducing risks to communities and economies while preserving or restoring essential ecosystems and thus their benefits to human welfare (Figure 25.6).[7,77]

ASSESSING FLOOD EXPOSURE OF CRITICAL FACILITIES AND ROADS

NOAA's Critical Facilities Flood Exposure Tool provides an initial assessment of the risk to a community's critical facilities and roads within the "100-year" flood zone established by the Federal Emergency Management Agency (FEMA) (the 100-year flood zone is the areal extent of a flood that has a 1% chance of occurring or being exceeded in any given year). The tool helps coastal managers quickly learn which facilities may be at risk – providing information that can be used to increase flood risk awareness and to inform a more detailed analysis and ultimately flood risk reduction measures. The critical facilities tool was initially created to assist Mississippi/Alabama Sea Grant in conducting its "Coastal Resiliency Index: A Community Self-Assessment" workshops and is now available for communities nationwide. For additional information see: http://www.csc.noaa.gov/digitalcoast/tools/criticalfacilities.

Key Message 2: Economic Disruption

Nationally important assets, such as ports, tourism, and fishing sites, in already-vulnerable coastal locations, are increasingly exposed to sea level rise and related hazards. This threatens to disrupt economic activity within coastal areas and the regions they serve and results in significant costs from protecting or moving these assets.

In 2010, economic activity in shoreline counties accounted for approximately 66 million jobs and $3.4 trillion in wages[78] through diverse industries and commerce. In many instances, economic activity is fundamentally dependent on the physical and ecological characteristics of the coast. These features provide the template for coastal economic activities, including natural protection from waves, access to beaches, flat land for port development and container storage, and wetlands that support fisheries and provide flood protection.

More than 5,790 square miles and more than $1 trillion of property and structures are at risk of inundation from sea level rise of two feet above current sea level – an elevation which could be reached by 2050 under a high rate of sea level rise of approximately 6.6 feet by 2100,[16] 20 years later assuming a lower rate of rise (4 feet by 2100) (Ch. 2: Our Changing Climate), and sooner in areas of rapid land subsidence.[79,80] Roughly half of the vulnerable property value is located in Florida, and the most vulnerable port cities are Miami, Greater New York, New Orleans, Tampa-St. Petersburg, and Virginia Beach.[38,45,79,81]

Although comprehensive national estimates are not yet available, regional studies are indicative of the potential risk: the incremental annual damage of climate change to capital assets in the Gulf region alone could be $2.7 to $4.6 billion by 2030, and $8.3 to $13.2 billion by 2050; about 20% of these at-risk assets are in the oil and gas industry.[82] Investing approximately $50 billion for adaptation over the next 20 years could lead to approximately $135 billion in averted losses over the lifetime of adaptive measures.[82,83]


©Boston Globe via Getty Images

More than $1.9 trillion in imports came through U.S. ports in 2010, with commercial ports directly supporting more than 13 million jobs[78] and providing 90% of consumer goods.[84] Ports damaged during major coastal storms can be temporarily or permanently replaced by other modes of freight movement, but at greater cost (Ch. 5: Transportation). The stakes are high and resources exist for ports to take proactive adaptation steps, such as elevating and interconnecting port- and land-based infrastructure or developing offsite storage capability (off-dock intermodal yards) for goods and related emergency response procedures.[85] However, a recent survey showed that most U.S. ports have not yet taken actions to adapt their operations to rising seas, increased flooding, and the potential for more extreme coastal storms.[86]

Coastal recreation and tourism comprises the largest and fastest-growing sector of the U.S. service industry, accounting for 85% of the $700 billion annual tourism-related revenues,[5,88] making this sector particularly vulnerable to increased impacts from climate change.[89] Historically, development of immediate shoreline areas with hotels, vacation rentals, and other tourism-related establishments has frequently occurred without adequate regard for coastal hazards, shoreline dynamics (for example, inlet migration), or ecosystem health.[90] Hard shoreline protection against the encroaching sea (like building sea walls or riprap) generally aggravates erosion and beach loss and causes negative effects on coastal ecosystems, undermining the attractiveness of beach tourism. Thus, "soft protection," such as beach replenishment or conservation and restoration of sand dunes and wetlands, is increasingly preferred to "hard protection" measures. Increased sea level rise means sand replenishment would need to be undertaken more frequently, and thus at growing expense.[34,91,92,93]

Natural shoreline protection features have some capacity to adapt to sea level rise and storms (Figure 25.6) and can also provide an array of ecosystem services benefits[94] that may offset some maintenance costs. A challenge ahead is the need to integrate climate considerations (for example, temperature change and sea level rise) into coastal ecosystem restoration and conservation efforts,[95] such as those underway in the Gulf of Mexico, Chesapeake Bay, and Sacramento-San Joaquin Delta, to ensure that these projects have long-term effectiveness.

U.S. oceanic and Great Lakes coasts are important centers for commercial and recreational fishing due to the high productivity of coastal ecosystems. In 2009, the U.S. seafood industry supported approximately 1 million full- and part-time jobs and generated $116 billion in sales and $32 billion in income.[96] Recreational fishing also contributes to the economic engine of the coasts, with some 74 million saltwater fishing trips along U.S. coasts in 2009 generating $50 billion in sales and supporting over 327,000 jobs.[96] Climate change threatens to disrupt fishing operations through direct and indirect impacts to fish stocks (for example, temperature-related shifts in species ranges, changes in prey availability, and loss of coastal nursery habitat) as well as storm-related disruptions of harbor installations (Ch. 24: Oceans).

Coast-to-Inland Economic Connections

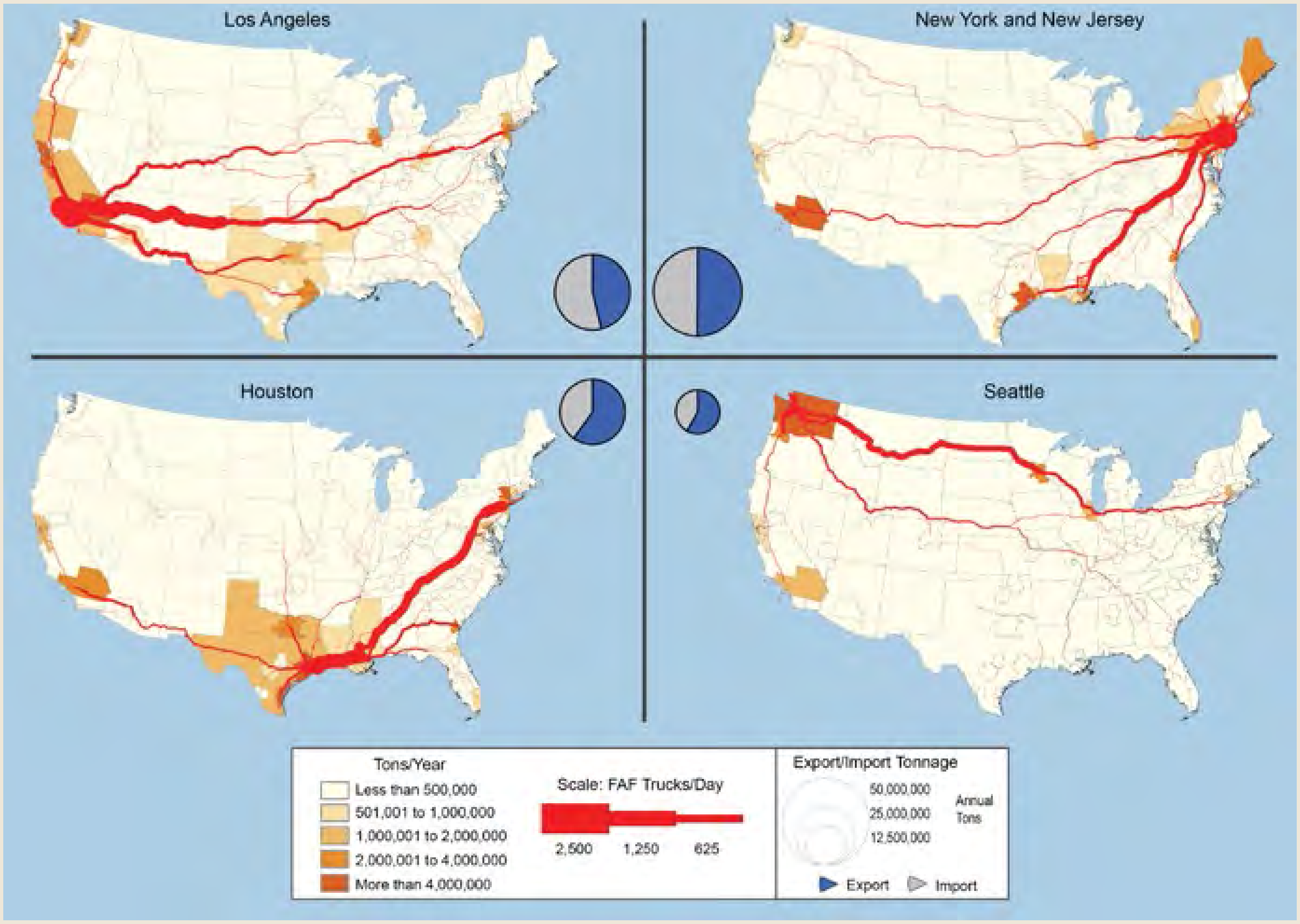

Figure 25.7. Ports are deeply interconnected with inland areas through the goods imported and exported each year. Climate change impacts on ports can thus have far-reaching implications for the nation's economy. These maps show the exports and imports in 2010 (in tons/year) and freight flows (in trucks per day) from four major U.S. ports to other U.S. areas designated in the U.S. Department of Transportation's Freight Analysis Framework (FAF): Los Angeles, Houston, New York/New Jersey, and Seattle. Note: Highway Link Flow less than 5 FAF Trucks/Day are not shown. (Figure source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, version 3.4, 2012).[87]

Key Message 3: Uneven Social Vulnerability

Socioeconomic disparities create uneven exposures and sensitivities to growing coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable people from coastal areas.

In 2010, almost 2.8% of the U.S. population, or more than 8.6 million Americans, lived within the area subject to coastal floods that have at least a 1% chance of occurring in any one year.[97,98] More than 120 million Americans live in counties that border the open ocean or Great Lakes coasts and/or have a 100-year coastal floodplain within them.[98] Two trends will place even more people at risk in the future: 1) the expansion of the floodplain as sea level rises, and 2) the continuing immigration of people to coastal areas.

By 2100, the fraction of the U.S. population living in coastal counties is expected to increase by 50% (46.2 million) to 144% (131.2 million) depending on alternative projections of future housing.[99] While specific population projections for future 100-year flood zones are only available for some locations,[100] many of these new arrivals can be expected to locate in high-hazard areas. Thus, coastal population densities, along with increasing economic development, will continue to be an important factor in the overall exposure to climate change.[3,7,39,101]

Despite persistent beliefs that living on the coast is reserved for the wealthy,[79,102] there are large social disparities in coastal areas that vary regionally.[41,103] Full understanding of risk for coastal communities requires consideration of social vulnerability factors limiting people's ability to adapt. These factors include lower income; minority status; low educational achievement; advanced age; income dependencies; employment in low-paying service, retail, and other sectors, as well as being often place-bound; less economically and socially mobile; and much less likely to be insured than wealthy property owners (see panel (a) in Figure 25.4).[104]

For example, in California, an estimated 260,000 people are currently exposed to a 100-year flood; this number could increase to 480,000 by 2100 as a result of a 4.6 foot sea level rise alone (roughly equivalent to the high end of the 1 to 4 foot range of sea level rise projections, Ch.2: Our Changing Climate).[38] Approximately 18% of those exposed to high flood risk by the end of this century also are those who currently fall into the "high social vulnerability" category.[81] This means that while many coastal property owners at the shorefront tend to be less socially vulnerable, adjacent populations just inland are often highly vulnerable.

The range of adaptation options for highly socially vulnerable populations is limited.[81] Native communities in Alaska, Louisiana, and other coastal locations already face this challenge today (see "Unique Challenges for Coastal Tribes" and Ch. 12: Indigenous Peoples).[105,106] As sea level rises faster and coastal storms, erosion, and inundation cause more frequent or widespread threats, relocation (also called (un)managed retreat or realignment), while not a new strategy in dynamic coastal environments, may become a more pressing option. In some instances relocation may become unavoidable, and for poorer populations sooner than for the wealthy. Up to 50% of the areas with high social vulnerability face the prospect of unplanned displacement under the 1 to 4 foot range of projected sea level rise (Ch.2: Our Changing Climate), for several key reasons: they cannot afford expensive protection measures themselves, public expense is not financially justified (often because social, cultural, and ecological factors are not considered), or there is little social and political support for a more orderly retreat process. By contrast, only 5% to 10% of the low social vulnerability areas are expected to face relocation.[41] This suggests that climate change could displace many socially vulnerable individuals and lead to significant social disruptions in some coastal areas.[107,108,109]

UNIQUE CHALLENGES FOR COASTAL TRIBES

Coastal Native American and Native Alaskan people, with their traditional dependencies upon natural resources and specific land areas, exhibit unique vulnerabilities. Tribal adaptation options can be limited because tribal land boundaries are typically bordered by non-reservation lands, and climate change could force tribes to abandon traditionally important locations, certain cultural practices, and natural resources on which they depend (Ch. 12: Indigenous Peoples).[110] Coastal food sources are also threatened, including salmon and shellfish. Climate change could affect other food species as well, worsening already existing health problems such as obesity, diabetes, and cancer.

Tribes pride themselves, however, for their experience and persistence in adapting to challenging situations. Some tribes are exploring unique adaptation approaches. In Louisiana's Isle de Jean Charles, for example, the Biloxi-Chitimacha-Choctaw Indian community partnered with a local academic center and a religious congregation to work toward relocating scattered tribal members with those seeking a communal safe haven, while working to save their ancestral land – aiming for community and cultural restoration and for the redevelopment of traditional livelihoods.[108,111]

Key Message 4: Vulnerable Ecosystems

Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.

Coastal ecosystems provide a suite of valuable benefits (ecosystem services) on which humans depend, including reducing the impacts from floods, buffering from storm surge and waves, and providing nursery habitat for important fish and other species, water filtration, carbon storage, and opportunities for recreation and enjoyment (Figure 25.8).[95,112,113]

However, many of these ecosystems and the services they provide are rapidly being degraded by human impacts, including pollution, habitat destruction, and the spread of invasive species. For example, 75% of U.S. coral reefs in the Atlantic, Caribbean, and Gulf of Mexico are already in "poor" or "fair" condition;[114,115] all Florida reefs are currently rated as "threatened."[116] Coastal barrier ecosystems continue to be degraded by human development, even in cases where development has slowed (for example, Crawford et al. 2013; Feagin et al. 2010b [117]). Coastal wetlands are being lost at high rates in southeastern Louisiana (Figure 25.9).[118] In addition, the incidence of low-oxygen "dead zones" in coastal waters has increased 30-fold in the U.S. since 1960, with over 300 coastal water bodies now experiencing stressful or lethal oxygen levels (Ch. 8: Ecosystems).[119]

These existing stresses on coastal ecosystems will be exacerbated by climate change effects, such as increased ocean temperatures that lead to coral bleaching,[30] altered river flows affecting the health of estuaries,[121] and acidified waters threatening shellfish.[122] Climate change affects the survival, reproduction, and health of coastal plants and animals in different ways. For example, changes in the timing of seasonal events (such as breeding and migration), shifts in species distributions and ranges, changes in species interactions, and declines in biodiversity all combine to produce fundamental changes in ecosystem character, distribution, and functioning.[28] Species with narrow physiological tolerance to change, low genetic diversity, specialized resource requirements, and poor competitive abilities are particularly vulnerable.[123,124] Where the rate of climate change exceeds the pace at which plants and animals can acclimate or adapt, impacts on coastal ecosystems will be profound.[35,125,126] For example, high death rates of East Coast intertidal mussels at their southern range boundary have occurred because of rising temperatures between 1956 and 2007.[127] The presence of physical barriers (for example, hardened shorelines or reduced sediment availability) and other non-climatic stressors (such as pollution, habitat destruction, and invasive species) will further exacerbate the ecological impacts of climate change and limit the ability of these ecosystems to adapt.[128,129,130] Onshore migration of coastal marshes as sea level rises is often limited by bulkheads or roads (a phenomenon often called "coastal squeeze"), ultimately resulting in a reduction in wetland area.[35,126,128,131,132,133]

Of particular concern is the potential for coastal ecosystems to cross thresholds of rapid change ("tipping points"), beyond which they exist in a dramatically altered state or are lost entirely from the area; in some cases, these changes will be irreversible.[134] These unique, "no-analog" environments present serious challenges to resource managers, who are confronted with conditions never seen before.[135,136,137] The ecosystems most susceptible to crossing such tipping points are those that have already lost some of their resilience due to degradation or depletion by non-climatic stressors.[138] Certain coastal ecosystems are already rapidly changing as a result of interactions between climatic and non-climatic factors, and others have already crossed tipping points. Eelgrass in the Chesapeake Bay died out almost completely during the record-hot summer of 2005, when temperatures exceeded the species' tolerance threshold of 86°F,[139] and subsequent recovery has been poor.[140] Severe low-oxygen events have emerged as a new phenomenon in the Pacific Northwest due to changes in the timing and duration of coastal upwelling.[32,141] These have led to high mortality of Dungeness crabs[33] and the temporary disappearance of rockfish,[32] with consequences for local fisheries. Reducing non-climatic stressors at the local scale can potentially prevent crossing some of these tipping points.[142]

Coastal Ecosystem Services

Figure 25.8. Coastal ecosystems provide a suite of valuable benefits (ecosystem services) on which humans depend for food, economic activities, inspiration, and enjoyment. This schematic illustrates many of these services situated in a Pacific or Caribbean island setting, but many of them can also be found along mainland coastlines.

Projected Land Loss from Sea Level Rise in Coastal Louisiana

Figure 25.9. These maps show expected future land change in coastal Louisiana under two different sea level rise scenarios without protection or restoration actions. Red indicates a transition from land (either wetlands or barrier islands) to open water. Green indicates new land built over previously open water. Land loss is influenced by factors other than sea level rise, including subsidence, river discharge and sediment load, and precipitation patterns. However, all these factors except sea level rise were held constant for this analysis. The panel on the left shows land change with a sea level rise of 10.6 inches between 2010 and 2060, while the one on the right assumes 31.5 inches of sea level rise for the same period. These amounts of sea level rise are within the projected ranges for this time period (Ch. 2: Our Changing Climate). (Figure source: State of Louisiana, reprinted with permission[120]).

Key Message 5: The State of Coastal Adaptation

Leaders and residents of coastal regions are increasingly aware of the high vulnerability of coasts to climate change and are developing plans to prepare for potential impacts on citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.

Considerable progress has been made since the last National Climate Assessment in both coastal adaptation science and practice (Figure 25.4, panel (d)), though significant gaps in understanding, planning, and implementation remain.[20,143,144,145] U.S. coastal managers pay increasing attention to adaptation, but are mostly still at an early stage of building their capacities for adaptation rather than implementing structural or policy changes (Ch. 28: Adaptation).[20,146,147] Although many non-structural (land-use planning, fiscal, legal, and educational) and structural adaptation tools are available through the Coastal Zone Management Act, Coastal Barriers Resources Act, and other frameworks, and while coastal managers are well familiar with these historical approaches to shoreline protection, they are less familiar with some of the more innovative approaches to coastal adaptation, such as rolling easements, ecosystem-based adaptation, or managed realignment.[109,131,144,148] Federal, state, and local management approaches have also been found to be at odds at times,[149] making successful integration of adaptation more difficult.[145] There is only limited evidence of more substantial ("transformational") adaptation occurring, that is, of adaptations that are "adopted at a much larger scale, that are truly new to a particular region or resource system, and that transform places and shift locations,"[150] such as relocation of communities in coastal Alaska and Louisiana (Ch. 22: Alaska).[83,109,150,151] Although more research is needed, reasons for the limited transformational adaptation to date may include the relatively early stage of recognizing climate change and sea level rise risks, the perception that impacts are not yet severe enough, and the fact that social objectives can still be met.[152]

Coastal leaders and populations, however, are increasingly concerned about climate-related impacts and support the development of adaptation plans,[153,154,155] but support for development restrictions or managed retreat is limited.[156,157,158] Economic interests and population trends tend to favor continued (re)development and in-fill in near-shore locations. Current disaster recovery practices frequently promote rapid rebuilding on-site with limited consideration for future conditions[159] despite clear evidence that more appropriate siting and construction can substantially reduce future losses.[160,161]

Enacting measures that increase resilience in the face of current hazards, while reducing long-term risks due to climate change, continues to be challenging.[162,163,164] This is particularly difficult in coastal flood zones that are subject to a 1%

or greater chance of flooding in any given year, including those areas that experience additional hazards from wave action. According to FEMA and policy/property data maintained by the National Flood Insurance Program's (NFIP) Bureau and Statistical Agent, nearly half of the NFIP's repetitive flood losses occur in those areas.[165,166] A robust finding is that the cost of inaction is 4 to 10 times greater than the cost associated with preventive hazard mitigation.[79,160] Even so, prioritizing expenditures now whose benefits accrue far in the future is difficult.[167] Moreover, cumulative costs to the economy of responding to sea level rise and flooding events alone could be as high as $325 billion by 2100 for 4 feet of sea level rise, with $130 billion expected to be incurred in Florida and $88 billion in the North Atlantic region.[80] The projected costs associated with one foot of sea level rise by 2100 are roughly $200 billion. These figures only cover costs of beach nourishment, hard protective structures, and losses of inundated land and property where protection is not warranted, but exclude losses of valuable ecosystem services, as well as indirect losses from business disruption, lost economic activity, impacts on economic growth, or other non-market losses.[80,168,169] Such indirect losses, even in regions generally well prepared for disaster events, can be substantial (in the case of Superstorm Sandy, followed by a nor'easter, in fall 2012, insured losses and wider economic damages added up to at least $65 billion).[170] Sequences of extreme events that occur over a short period not only reduce the time available for natural and social systems to recover and for adaptation measures to be implemented, but also increase the cumulative effect of back-to-back extremes compared to the same events occurring over a longer period.[164,171] The cost of managed retreat requires further assessment.

Property insurance can serve as an important mode of financial adaptation to climate risks,[172] but the full potential of leveraging insurance rates and availability has not yet been realized.[7,173,174] The Government Accountability Office (GAO) listed the National Flood Insurance Program as a "high-risk area" for the first time in 2006, indicating its significance in terms of federal fiscal exposure (nearly $1.3 trillion in 2012).[175] In the context of identifying climate change as a high risk to federal operations, the GAO in 2013 singled out the NFIP again, recognizing growing risks and liabilities due to climate change and sea level rise and the increase in erosion and flooding they entail.[176] While insured assets in coastal areas represent only a portion of this total liability, taxpayers are responsible, via the NFIP, for more than $510 billion of insured assets in the coastal Special Flood Hazard Area (SFHA) alone.[53,177] A number of reforms in the NFIP have been enacted in 2012 to ensure that the program is more fiscally sound and hazard mitigation is improved, though various challenges remain.[178]

Climate adaptation efforts that integrate hazard mitigation, natural resource conservation, and restoration of coastal ecosystems can enhance ecological resilience and reduce the exposure of property, infrastructure, and economic activities to climate change impacts (Figure 25.6).[113,179] Yet, the integration and translation of scientific understanding of the benefits provided by ecosystems into engineering design and hazard management remains challenging.[180] Moreover, interdependencies among functioning infrastructure types and coastal uses require an integrated approach across scientific disciplines and levels of government, but disconnected scientific efforts and fragmented governance at the managerial, financial, and regulatory levels, and narrow professional training, job descriptions, and agency missions pose significant barriers (Ch. 11: Urban; Ch. 28: Adaptation).[145,181,182] Adaptation efforts to date that have begun to connect across jurisdictional and departmental boundaries and create innovative solutions are thus extremely encouraging.[7,145,183,184]

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PHOTO CREDITS

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the assessment process was a Chapter Lead Authors meeting held in St. Louis, Missouri in April 2012. The key messages were initially developed at this meeting. Key vulnerabilities were operationally defined as those challenges that can fundamentally undermine the functioning of human and natural coastal systems. They arise when these systems are highly exposed and sensitive to climate change and (given present or potential future adaptive capacities) insufficiently prepared or able to respond. The vulnerabilities that the team decided to focus on were informed by ongoing interactions of the author team with coastal managers, planners, and stakeholders, as well as a review of the existing literature. In addition, the author team conducted a thorough review of the technical input reports (TIR) and associated literature, including the coastal zone foundational TIR prepared for the National Climate Assessment (NCA).[7] Chapter development was supported by numerous chapter author technical discussions via teleconference from April to June 2012.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, erosion, and other climate-related changes.

Description of evidence base

Coastal infrastructure is defined here to include buildings, roads, railroads, airports, port facilities, subways, tunnels, bridges, water supply systems, wells, sewer lines, pump stations, wastewater treatment plants, water storage and drainage systems, port facilities, energy production and transmission facilities on land and offshore, flood protection systems such as levees and seawalls, and telecommunication equipment. Lifelines are understood in the common usage of that term in hazards management.

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report[7] as well as a technical input report on infrastructure.[48] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant scientific literature. Additional evidence is provided in other chapters on hurricanes (Ch. 2: Our Changing Climate, Key Message 8), global sea level rise (Ch. 2: Our Changing Climate, Key Message 10), water supply vulnerabilities (Ch. 3: Water); key coastal transportation vulnerabilities (Ch. 5: Transportation), and energy-related infrastructure (Ch. 4: Energy). This key message focuses mainly on water supply and energy infrastructure and evacuation routes, as these constitute critical lifelines.

The evidence base for exposure, sensitivity, and adaptive capacity to higher sea levels and storm surges is very strong, both from empirical observation and historical experience and from studies projecting future impacts on critical coastal infrastructure. There are numerous publications concerning the effects of sea level rise and storm surges on roadways, coastal bridges, and supply of refined products.[7,38,40,64,93,147,162] The information on roadways came from various reports (for example, DOT 2012; Transportation Research Board 2011; NPCC 2009, 2010[55,56,184]) and other publications (for example, State of Louisiana 2012[83]). The impact on coastal bridges is documented in U.S. Department of Transportation reports.[55,59] A number of publications explored the impacts on supply of refined oil-based products such as gasoline.[73]

The evidence base is moderate for the interaction of inland and coastal flooding. There are many and recent publications concerning impacts to wastewater treatment plants[47,61] and drainage systems.[18,27,64,65,70] These impacts lead to increased risk of urban flooding and disruption of essential services to urban residents.

New information and remaining uncertainties

The projected rate of sea level rise (SLR) is fully accounted for through the use of common scenarios. We note, however, that there is currently limited impacts literature yet that uses the lowest or highest 2100 scenario and none that specifically use the broader range of SLR (0.2 to 2 meters, or 0.7 to 6.6 feet, by 2100) [16] and NCA land-use scenarios (60% to 164% increase in urban and suburban land area).[185]

The severity and frequency of storm damage in any given location cannot yet be fully accounted for due to uncertainties in projecting future extratropical and tropical storm frequency, intensity, and changes in storm tracks for different regions (Ch. 2: Our Changing Climate).[7]

The timely implementation and efficacy of adaptation measures, including planned retreat, in mitigating damages is accounted for in the underlying literature (for example, by varying assumptions about the timing of implementation of adaptation measures and the type of adaptation measures) such as hard protection, elevation, relocation, or protection through wetlands and dunes in front of the infrastructure in question) (for example, Aerts and Botzen 2012; Biging et al. 2012; Bloetscher et al. 2011; Heberger et al. 2009; Irish et al. 2010; Kirshen et al. 2011[18,38,44,45,47]). However, such studies can only test the sensitivity of conclusions to these assumptions; they do not allow statements about what is occurring on the ground.

Additional uncertainties arise from the confluence of climate change impacts from the inland and ocean side, which have yet to be studied in an integrated fashion across different coastal regions of the United States.

Assessment of confidence based on evidence

Given the evidence base, the large quantity of infrastructure (water-related infrastructure, energy infrastructure, and the 60,000 miles of coastal roads) in the U.S. coastal zone, and the directional trend at least of sea level rise and runoff associated with heavy precipitation events, we have **very high** confidence that these types of infrastructure in the coastal zone are increasingly vulnerable.

Confidence Level

Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Nationally important assets, such as ports, tourism and fishing sites, in already-vulnerable coastal locations, are increasingly exposed to sea level rise and related hazards. This threatens to disrupt economic activity within coastal areas and the regions they serve and results in significant costs from protecting or moving these assets.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, as well as the extant scientific literature.

The evidence base for increased exposure to assets is strong. Many publications have assessed at-risk areas (for example, Biging et al. 2012; Cooley et al. 2012; Heberger et al. 2009; Neumann et al. 2010a[38,45,79,81]). Highly reliable economic activity information is available from recurring surveys conducted by the National Oceanographic and Atmospheric Administration (NOAA) and others, and asset exposure is conclusively demonstrated by historical information (from storm and erosion damage), elevation data (in Geographic Information System (GIS)-based, LIDAR, and other forms), and numerous vulnerability and adaptation studies of the built environment. Further evidence is provided in technical input reports and other NCA chapters on infrastructure and urban systems (Ch. 11: Urban),[48] transportation (Ch. 5: Transportation),[55] and energy (Ch. 4: Energy). A number of studies in addition to the ones cited in the text, using various economic assumptions, aim to assess the cost of protecting or relocating coastal assets and services. Many publications and reports explore the cost of replacing services offered by ports,[55,91] though one study[186] notes that few ports are implementing adaptation practices to date. The economic consequences of climate change on tourism are supported by a number of recent studies.[89,90,91,93] The threats of climate change on fishing have been explored in the coastal zone technical input report.[7]

Additional evidence comes from empirical observation: public statements by private sector representatives and public officials indicate high awareness of economic asset exposure and a determination to see those assets protected against an encroaching sea, even at high cost (New York City, Miami Dade County, San Francisco airport, etc.). The economic value of exposed assets and activities is frequently invoked when they get damaged or interrupted during storm events (for example, Hallegattee 2012[169]). Threats to economic activity are also consistently cited as important to local decision-making in the coastal context (for example, Titus et al. 2009[109]).

New information and remaining uncertainties

The projected rate of sea level rise is fully accounted for through the use of common scenarios. We note, however, that there is currently limited impacts literature that uses the lowest or highest scenario for 2100, and no studies that specifically use the broader range of SLR (0.7 to 6.6 feet,) and NCA land-use scenarios (60% to 164% increase in urban and suburban land area).[185]

The projected severity and frequency of storm damage in any given location cannot yet be fully accounted for due to uncertainties in projecting future extratropical and tropical storm frequency, intensity, and changes in storm tracks for different regions.[7]

The timely implementation and efficacy of adaptation measures, including planned retreat, in mitigating damages are accounted for in the underlying literature (for example, by varying assumptions about the timing of implementation of adaptation measures, the type of adaptation measures, and other economic assumptions such as discount rates). However, such studies can only test the sensitivity of conclusions to these assumptions; they do not allow statements about what is occurring on the ground. Well-established post-hoc assessments[160] suggest that hazard mitigation action is highly cost-effective (for every dollar spent, four dollars in damages are avoided). A more recent study suggests an even greater cost-effectiveness.[79]

Assessment of confidence based on evidence

Given the evidence base, the well-established accumulation of economic assets and activities in coastal areas, and the directional trend of sea level rise, we have **very high** confidence in the main conclusion that resources and assets that are nationally important to economic productivity are threatened by SLR and climate change.

While there is currently no indication that the highest-value assets and economic activities are being abandoned in the face of sea level rise and storm impacts, we have **very high** confidence that the cost of protecting these assets in place will be high, and that the cost will be higher the faster sea level rises relative to land.

We have **very high** confidence that adequate planning and arrangement for future financing mechanisms, timely implementation of hazard mitigation measures, and effective disaster response will keep the economic impacts and adaptation costs lower than if these actions are not taken.

We are not able to assess timing or total cost of protecting or relocating economic assets with any confidence at this time, due to uncertainties in asset-specific elevation above sea level, in the presence and efficacy of protective measures (at present and in the future), in the feasibility of relocation in any particular case, and uncertainties in future storm surge heights and storm frequencies.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Socioeconomic disparities create uneven exposures and sensitivities to growing coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable people from coastal areas.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature.

Evidence base is moderate: assessment of the social vulnerability to coastal impacts of climate change is a comparatively new research focus in the United States, and clearly an advance since the prior NCA.[187] There are currently multiple published, peer-reviewed studies, by different author teams, using different vulnerability metrics, which all reach the same conclusion: economically and socially vulnerable individuals and communities face significant coastal risks and have a lower adaptive capacity than less socially vulnerable populations. Studies have shown that the U.S. coastal population is growing [99] and have assessed the importance of this population for climate change exposure.[39,101] The social factors that play key roles in coastal vulnerability are detailed in numerous publications.[81,104,188]

There is an additional body of evidence emerging in the literature that also supports this key message, namely the growing literature on "barriers to adaptation," particularly from studies conducted here in the United States.[7,81,105,145,189] This literature reports on the limitations poorer communities face at present in beginning adaptation planning, and on the challenges virtually all communities face in prioritizing adaptation and moving from planning to implementation of adaptation options.

There is empirical evidence for how difficult it is for small, less wealthy communities (for example, the Native communities in Alaska or southern Louisiana) to obtain federal funds to relocate from eroding shorelines.[107,108] Eligibility criteria (positive benefit-cost ratios) make it particularly difficult for low-income communities to obtain such funds; current federal budget constraints limit the available resources to support managed retreat and relocation.[166,173] The recent economic hardship has placed constraints even on the richer coastal communities in the U.S. in developing and implementing adaptation strategies, for example in California.[145] While the economic situation, funding priorities, or institutional mechanisms to provide support to socially vulnerable communities will not remain static over time, there is no reliable scientific evidence for how these factors may change in the future.

New information and remaining uncertainties

The body of research on this topic is largely new since the prior NCA in 2009.[187] Each of the peer-reviewed studies discusses data gaps and methodological limitations, as well as the particular challenge of projecting demographic variables – a notoriously difficult undertaking – forward in time. While methods for population projections are well established (typically using housing projections), those, in turn, depend on more difficult to make assumptions about fertility, migration, household size, and travel times to urban areas. The conclusion is limited by uneven coverage of in-depth vulnerability studies; although those that do exist are consistent with and confirm the conclusions of a national study.[41] This latter study was extended by applying the same approach, data sources, and methodology to regions previously not covered, thus closing important informational gaps (Hawai'i, Alaska, the Great Lakes region). Data gaps remain for most coastal locations in the Pacific Islands, Puerto Rico, and other U.S. territories.

The most important limit on understanding is the current inability to project social vulnerability forward in time. While some social variables are more easily predicted (for example, age and gender distribution) than others (for example, income distribution, ethnic composition, and linguistic abilities), the predictive capability declines the further out projections aim (beyond 2030 or 2050). Further, it is particularly difficult to project these variables in specific places subject to coastal hazards, as populations are mobile over time, and no existing model reliably predicts place-based demographics at the scale important to these analyses.

Assessment of confidence based on evidence

We have **high** confidence in this conclusion, as it is based on well-accepted techniques, replicated in several place-based case studies, and on a nationwide analysis, using reliable Census data. Consistency in insights and conclusions in these studies, and in others across regions, sectors, and nations, add to the confidence. The conclusion does involve significant projection uncertainties, however, concerning where socially vulnerable populations will be located several decades from now. Sensitivity analysis of this factor, and overall a wider research base is needed, before a higher confidence assessment can be assigned.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature.

Evidence base is strong for this part of the key message: "Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses."

The degradation and depletion of coastal systems due to human stresses (for example, pollution, habitat destruction, and overharvesting) has been widely documented throughout the U.S. and the world.[68,115,116,118,119] The degree of degradation varies based on location and level of human impact. However, evidence of degradation is available for all types of U.S. coastal ecosystems, from coral reefs to seagrasses and rocky shores. Human stresses can be direct (for example, habitat destruction due to dredging of bays) or indirect (for example, food web disruption due to overfishing). There is also consistent evidence that ecosystems degraded by human activities are less resilient to changes in climatic factors, such as water temperature, precipitation, and sea level rise (for example, Gedan et al. 2009; Glick et al. 2011; Williams and Grosholz 2008[128,129,130]).

Evidence base is strong: "climate change will result in further reduction or loss of the services that these ecosystems provide."

The impacts of changing coastal conditions (for example, changes associated with altered river inflows, higher temperatures, and the effects of high rates of relative sea level rise) on coastal ecosystems and their associated services have been extensively documented through observational and empirical studies, including recent publications.[28,121,122,123,129,133] Many models of coastal ecosystem responses to climatic factors have been well-validated with field data. Given the existing knowledge of ecosystem responses, future climate projections, and the interactions with non-climatic stressors that further exacerbate climatic impacts, evidence is strong of the potential for further reduction and/or loss of ecosystem services.

Evidence is suggestive: "including potentially irreversible impacts."

Severe impacts (for example, mass coral bleaching events and rapid species invasions) have been extensively documented for U.S. coastal ecosystems. Many experts have suggested that some of these impacts may be irreversible[134] and never before seen conditions have been documented.[136,137] Recovery may or may not be possible in different instances; this depends on factors that are not well-understood, such as the adaptive capacity of ecosystems, future projections of change that consider interactions among multiple climatic and non-climatic human alterations of systems, the dynamics and persistence of alternative states that are created after a regime shift has occurred, and whether or not the climatic and/or non-climatic stressors that lead to impacts will be ameliorated.[32,33,138,139,140,141]

New information and remaining uncertainties

Since the 2009 NCA,[187] new studies have added weight to previously established conclusions. The major advance lies in the examination of tipping points for species and entire ecosystems (for example, Barnosky et al. 2012; Folke et al. 2004; Foti et al. 2013; Hoegh-Guldberg and Bruno 2010[134,135,137,138]). Existing uncertainties and future research needs were identified through reviewing the NCA technical inputs and other peer-reviewed, published literature on these topics, as well as through our own identification and assessment of knowledge gaps.

Key uncertainties in our understanding of ecosystem impacts of climate change in coastal areas are associated with:

- the interactive effects and relative contributions of multiple climatic and non-climatic stressors on coastal organisms and ecosystems;
- how the consequences of multiple stressors for individual species combine to affect community- and ecosystem-level interactions and functions;
- the projected magnitude of coastal ecosystem change under different scenarios of temperature change, sea level rise, and land-use change, particularly given the potential for feedbacks and non-linearities in ecosystem responses;
- the potential adaptive capacity of coastal organisms and ecosystems to climate change;
- trajectories, timeframes, and magnitudes of coastal ecosystem recovery;
- the dynamics and persistence of alternative states that are created after ecosystem regime shifts have occurred; and
- the potential and likelihood for irreversible climate-related coastal ecosystem change.

In general, relatively little work to date has been conducted to project future coastal ecosystem change under integrative scenarios of temperature change, sea level rise, and changes in human uses of, and impacts to, coastal ecosystems (for example, through land-use change). Advancing understanding and knowledge associated with this key uncertainty, as well as the others included in the above list, would be fostered by additional research.

Assessment of confidence based on evidence

We have **very high** confidence that coastal ecosystems are particularly vulnerable to climate change because they have already been dramatically altered by human stresses, as documented in extensive and conclusive evidence.

We have **very high** confidence that climate change will result in further reduction or loss of the services that these ecosystems provide, as there is extensive and conclusive evidence related to this vulnerability.

We have **high** confidence that climatic change will include "potentially irreversible impacts." Site-specific evidence of potentially irreversible impacts exists in the literature. This vulnerability is frequently identified by studies of coastal ecosystems. However, methods, research, and models are still being developed for understanding, documenting, and predicting potentially irreversible impacts across all types of coastal ecosystems.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Leaders and residents of coastal regions are increasingly aware of the high vulnerability of coasts to climate change, and are developing plans to prepare for potential impacts on citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature.

Evidence base is moderate to strong: the results on which this key message relies are based on case studies, direct observation and "lessons learned" assessments from a wide range of efforts, surveys, and interview studies in ongoing adaptation efforts around the country.[154] There has been some planning for remediating climate change impacts, including recent publications[144,153,163,164] and there are publications on the lower social acceptance of certain adaptation option (for example, Finzi Hart et al. 2012; Peach 2012[144,158]) and on the many barriers that affect adaptation.[145,181,182]

In addition, there is confirming evidence of very similar findings from other locations outside the U.S. (some, from Canada, were also submitted as technical input reports to the NCA), such as the United Kingdom, continental Europe, Australia, and others.[157,181]

New information and remaining uncertainties

Adaptation is a rapidly spreading policy and planning focus across coastal America. This was not previously captured or assessed in the 2009 NCA[187] and is thus a major advance in understanding, including what adaptation activities are underway, what impedes them, and how coastal stakeholders view and respond to these emerging adaptation activities.

Given the local nature of adaptation (even though it frequently involves actors from all levels of government), it is difficult to systematically track, catalog, or assess progress being made on adaptation in coastal America. The difficulty, if not impossibility, of comprehensively tracking such progress has been previously acknowledged.[20] This conclusion is reiterated in the Adaptation chapter (Ch. 28) of this report.

While the findings and integrative key message stand on strong evidence, some uncertainties remain about U.S. coastal regions' adaptive capacity, the level of adoption of hazard mitigation and other adaptation strategies, and the extent and importance of barriers to adaptation.

Possibly the least well-understood aspect about coastal adaptation is how and when to undertake large-scale, transformational adaptation. Aside from the mentioned examples of relocation, no other examples exist at the present time, and further research is required to better understand how major institutional, structural, or social transformation might occur and what would be involved to realize such options.

Assessment of confidence based on evidence

We have **very high** confidence in this key message, as it is primarily based on studies using well-accepted social science research techniques (for example, surveys, interviews, and participant observation), replicated in several place-based case studies, and on a nationwide compilation of adaptation case studies. Consistency in insights and conclusions in these studies, and in others across regions, sectors, and nations, add to the confidence.

As described above, a comprehensive catalogue of all adaptation efforts, and of related challenges and lessons learned, is difficult if not impossible to ever obtain. Nevertheless, the emerging insights and evidence from different regions of the country provide considerable confidence that the situation is reasonably well captured in the documents relied on here. The coastal stakeholders represented among the authors of the foundational technical input report[7] confirmed the conclusions from their long-term experience in coastal management and direct involvement in adaptation efforts locally.

Moreover, evidence from other regions outside the U.S. adds weight to the conclusions drawn here.

RESPONSE STRATEGIES

People make choices every day about risks and benefits in their lives, weighing experience, information, and judgment as they consider the impacts of their decisions on themselves and the people around them. Similarly, people make choices that alter the magnitude of impacts resulting from current and future climate change. Using science-based information to anticipate future changes can help society make better decisions about how to reduce risks and protect people, places, and ecosystems from climate change impacts. Decisions made now and in the future will influence society's resilience to impacts of future climate change.

In recognition of the significance of these decisions, the National Climate Assessment presents information that is useful for a wide variety of decisions across regions and sectors, at multiple scales, and over multiple time frames. For the first time, the National Climate Assessment includes chapters on Decision Support, Mitigation, and Adaptation, in addition to identifying research needs associated with these topics.

As with other sections of this report, the linkages across and among these chapters are extremely important. There are direct connections between mitigation decisions (about whether and how to manage emissions of heat-trapping gases) and how much climate will change in the future. The amount of change that occurs will in turn dictate the amount of adaptation that will be required.

In the Decision Support chapter, a variety of approaches to bridge the gap between scientific understanding and decision-making are discussed, leading to the conclusion that there are many opportunities to help scientists understand the needs of decision-makers, and also to help decision-makers use available tools and information to reduce the risks of climate change. The Mitigation chapter describes emissions trajectories and assesses the state of mitigation activities. Policies already enacted and other factors lowered U.S. emissions in recent years, but achievement of a global emissions path consistent with the lower scenario (B1) analyzed in this assessment will require strenuous action by all major emitters. The Adaptation chapter assesses current adaptation activities across the United States in the public and private sectors, and concludes that although a lot of adaptation planning is being done, implementation lags significantly behind the scale of anticipated changes.

This report concludes with chapters on Research Needs to improve future climate and global change assessments and on the Sustained Assessment Process, which describes the rationale for ongoing assessment activity to achieve greater efficiency and better scientific and societal outcomes.

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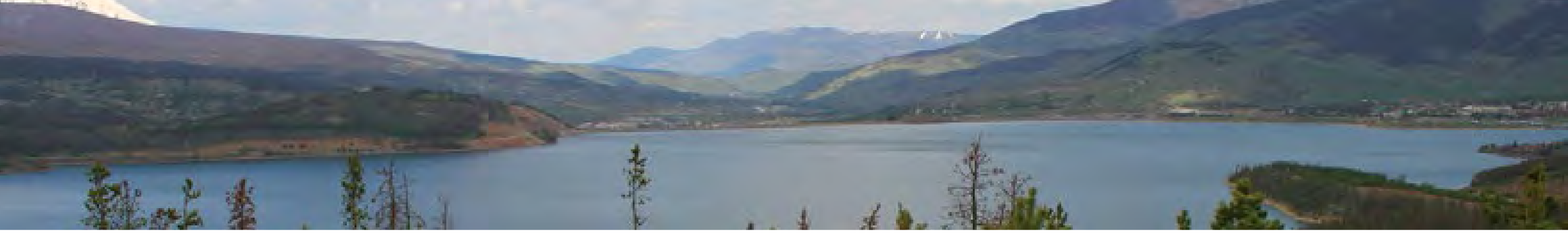

Climate Change Impacts in the United States

CHAPTER 26
DECISION SUPPORT
CONNECTING SCIENCE, RISK PERCEPTION, AND DECISIONS

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On the Web: http://nca2014.globalchange.gov/report/response-strategies/decision-support

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

26

DECISION SUPPORT:

CONNECTING SCIENCE, RISK PERCEPTION, AND DECISIONS

Key Messages

1. **Decisions about how to address climate change can be complex, and responses will require a combination of adaptation and mitigation actions. Decision-makers – whether individuals, public officials, or others – may need help integrating scientific information into adaptation and mitigation decisions.**
2. **To be effective, decision support processes need to take account of the values and goals of the key stakeholders, evolving scientific information, and the perceptions of risk.**
3. **Many decision support processes and tools are available. They can enable decision-makers to identify and assess response options, apply complex and uncertain information, clarify tradeoffs, strengthen transparency, and generate information on the costs and benefits of different choices.**
4. **Ongoing assessment processes should incorporate evaluation of decision support tools, their accessibility to decision-makers, and their application in decision processes in different sectors and regions.**
5. **Steps to improve collaborative decision processes include developing new decision support tools and building human capacity to bridge science and decision-making.**

After a long period of relative stability in the climate system, climate conditions are changing and are projected to continue to change (Ch. 2: Our Changing Climate). As a result, historically successful strategies for managing climate-sensitive resources and infrastructure will become less effective over time. Although decision-makers routinely make complex decisions under uncertain conditions, decision-making in the context of climate change can be especially challenging due to a number of factors. These include the rapid pace of changes in some physical and human systems, long time lags between human activities and response of the climate system, the high economic and political stakes, the number and diversity of potentially affected stakeholders, the need to incorporate uncertain scientific information of varying confidence levels, and the values of stakeholders and decision-makers.[1,2,3] The social, economic, psychological, and political dimensions of these decisions underscore the need for ways to improve communication of scientific information and uncertainties and to help decision-makers assess risks and opportunities.

Extensive literature and practical experience offer means to help improve decision-making in the context of climate variability and change. The decision-support literature includes topics such as decision-making frameworks, decision support tools, and decision support processes. These approaches can help evaluate the costs and benefits of alternative actions, communicate relative amounts of risk associated with different options, and consider the role of alternative institutions and governance structures. In particular, iterative decision processes that incorporate improving scientific information and learning though periodic reviews of decisions over time are helpful in the context of rapid changes in environmental conditions.[3,4] Some of the approaches described in this chapter can also help overcome barriers to the use of existing tools and improve communications among scientists, decision-makers, and the public.[5,6]

Focus of this chapter

This chapter introduces decision-making frameworks that are useful for considering choices about climate change responses through the complementary strategies of adaptation and mitigation. It also includes numerous examples in which decision support tools are being employed in making adaptation and mitigation decisions. It focuses on the processes that promote sustained interaction between decision-makers and the scientific/technical community. This chapter reviews the state of knowledge and practice in the context of managing risk. Extensive literature makes clear that in many cases, decisions aided by the types of approaches described here prove more successful than unaided decisions.[3,7] Because of space limitations, the chapter describes some general classes of tools but does not assess specific decision support tools.

What are the decisions and who are the decision-makers?

Decisions about climate change adaptation and mitigation are being made in many settings (Table 26.1). For example:

- The Federal Government is engaged in decisions that affect climate policy at the national and international level; makes regulatory decisions (for example, setting efficiency standards for vehicles); and makes decisions about infrastructure and technologies that may reduce risks associated with climate change for its own facilities and activities.
- State, tribal, and local governments are involved in setting policy about both emissions and adaptation activities in a variety of applications, including land use, renewable portfolio and energy efficiency standards, and investments in infrastructure and technologies that increase resilience to extreme weather events.
- Private-sector companies have initiated strategies to respond both to the risks to their investments and the business opportunities associated with preparing for a changing climate.
- Non-governmental organizations have been active in supporting decisions that integrate both adaptation and mitigation considerations, often in the context of promoting sustainability within economic sectors, communities, and ecosystems.

Individuals make decisions on a daily basis that affect their contributions to greenhouse gas emissions, their preparedness for extreme events, and the health and welfare of their families.[8]

Many decisions involve decision-makers and stakeholders at multiple scales and in various sectors. Effective decision support must link and facilitate interactions across different decision networks.[9]

Table 26.1. Examples of Decisions at Different Scales

Individuals ↓ ↓ Organizations ↓ ↓ Communities ↓ ↓ ↓ National Governments ↓ ↓ ↓ International Institutions	A farmer decides whether to adopt no-till agricultural practices.
	A private firm decides whether to invest in solar or wind energy.
	A city develops a plan to increase resiliency to coastal floods in light of projections for sea level rise.
	A government agency plans incentives for renewable energy to meet greenhouse gas reduction goals.
	A national government develops its positions for international climate negotiations, including what commitments the government should make with respect to reducing greenhouse gas emissions.
	A United Nations agency designs a long-term strategy to manage increased flows of refugees who are migrating in part due to desertification related to climate change.

What is decision support?

Decision support refers to “organized efforts to produce, disseminate, and facilitate the use of data and information” to improve decision-making.[3] It includes processes, decision support tools, and services. Some examples include methods for assessing tradeoffs among options, scenarios of the future used for exploring the impacts of alternative decisions, vulnerability and impacts assessments, maps of projected climate impacts, and tools that help users locate, organize, and display data in new ways. Outcomes of effective decision support processes include building relationships and trust that can support longer-term problem-solving capacity between knowledge producers and users; providing information that users regard as credible, useful, and actionable; and enhancing the quality of decisions.[3] Decision support activities that facilitate well-structured decision processes can result in consensus about defining the problems to be addressed, objectives and options for consideration, criteria for evaluation, potential opportunities and consequences, and tradeoffs (Figure 26.1).

Decision-Making Elements and Outcomes

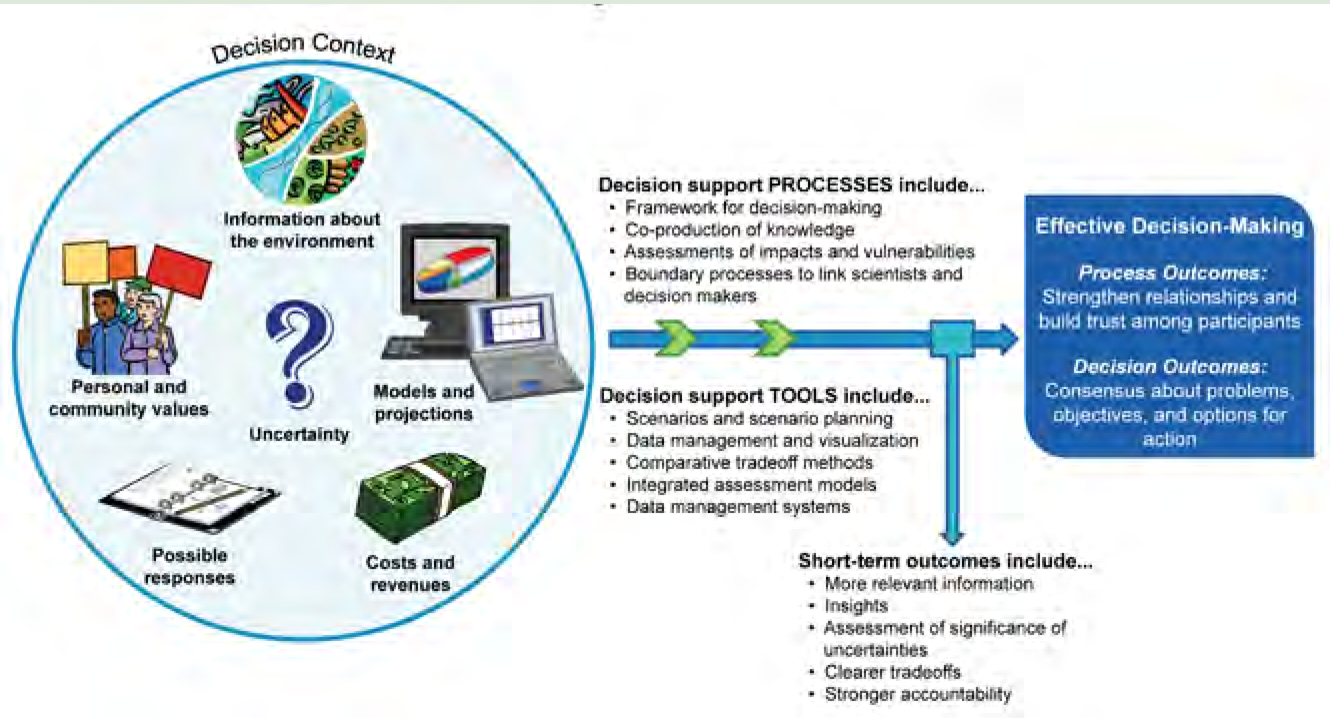


Figure 26.1. Decisions take place within a complex context. Decision support processes and tools can help structure decision-making, organize and analyze information, and build consensus around options for action.

Boundary Processes: Collaboration among Decision-Makers, Scientists, and Stakeholders

Incorporating the implications of climate change in decision-making requires consideration of scientific insights as well as cultural and social considerations, such as the values of those affected and cultural and organizational characteristics. Chapter 28 (Adaptation) addresses how some of these factors might be addressed in the context of adaptation. The importance of both scientific information and societal considerations suggests the need for the public, technical experts, and decision-makers to engage in mutual shared learning and shared production of relevant knowledge.[3,10] A major challenge in these engagements is communicating scientific information about the risks and uncertainties of potential changes in climate.[11]

Boundary Processes Linking
Decision-Makers and Scientific/Technical Experts

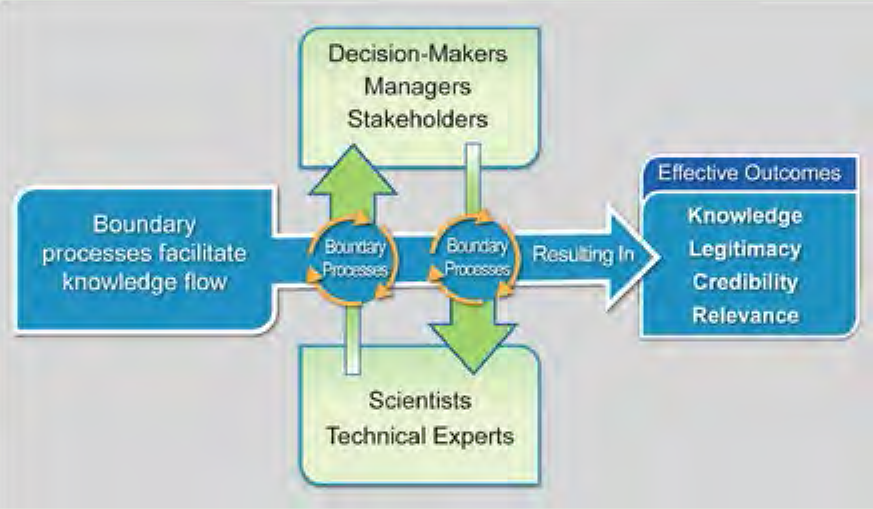
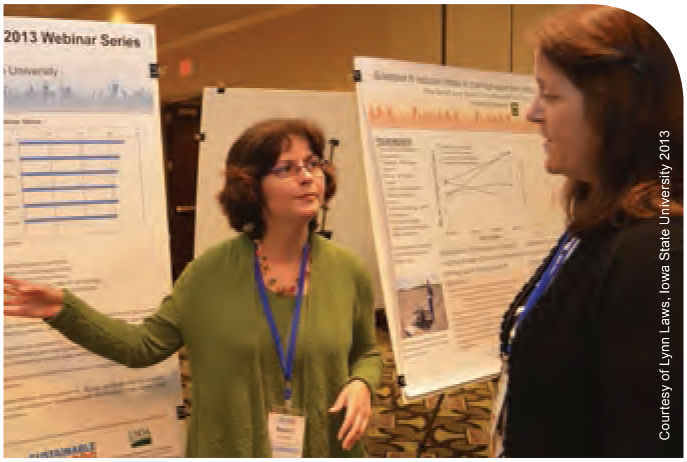


Figure 26.2. Boundary processes facilitate the flow of information and sharing of knowledge between decision-makers and scientists/technical experts. Processes that bring these groups together and help translate between different areas of expertise can provide substantial benefits.

Efforts to facilitate interactions among technical experts and members of the public and decision-makers are often referred to as "boundary processes" (Figure 26.2). Boundary processes and associated tools include, for example, joint fact finding, structured decision-making, collaborative adaptive management, and computer-aided collaborative simulation, each of which engages scientists, stakeholders, and decision-makers in ongoing dialog about understanding the policy problem and identifying what information and analyses are necessary to evaluate decision options.[12,13,14] The use of these kinds of processes is increasing in decision settings involving complex scientific information and multiple – sometimes competing – societal values and goals. Well-designed boundary processes improve the match between the availability of scientific information and capacity to use it and result in scientific information that is perceived as useful and applicable.

Though boundary processes developed to support climate-related decisions vary in their design, they all involve bringing together scientists, decision-makers, and citizens to collaborate in the scoping, conduct, and employment of technical and scientific studies to improve decision-making. Boundary processes can involve establishing specialized institutions, sometimes referred to as boundary organizations, to provide a forum for interaction amongst scientists and decision-makers.[15] One such boundary activity is the National Oceanic and Atmospheric Administration's (NOAA) Regional Integrated Science and Assessment (RISA) Program. Interdisciplinary RISA teams are largely based at universities and engage regional, state, and local governments, non-governmental organizations, and private sector organizations to address issues of concern to decision-makers and planners at the regional level. RISA teams help to build bridges across the scientist, decision-maker, and stakeholder divide.[16] Effective engagement may also occur through less formal approaches by incorporating boundary processes that bring scientists, stakeholders, and decision-makers together within a specific decision-making setting rather than relying on an independent boundary organization. Sustained conversations among scientists, decision-makers, and stakeholders are often necessary to frame issues and identify, generate, and use relevant information.[17]

Some analysts have emphasized the importance of boundary processes that are collaborative and iterative.[18] In one example, federal, state, and local agencies, water users, and other stakeholders are using a collaborative process to manage the Platte River to meet species protection goals and the needs of other water users. The Platte River Recovery Implementation Program brings together participants on an ongoing basis to help set goals, choose management options, and generate information about the effectiveness of their actions.[19] Scientists engaged in the process do not make policy decisions, but they engage directly with participants to help them frame scientific questions relevant to management choices, understand available information, design monitoring systems to assess outcomes of management actions, and generate new knowledge tailored to addressing key decision-maker questions. The process has helped participants move beyond disagreements about the water-flow needs of the endangered species and move to action. Through monitoring, participants will evaluate whether the water flows and other management practices are achieving the goals for species recovery set out in the Platte River Recovery Implementation Plan.



Courtesy of Lynn Laws, Iowa State University 2013

In a number of other examples, boundary processes involve the use of computer simulation models.[14] Scientists, stakeholders, and decision-makers develop a shared understanding of the problem and potential solutions by jointly designing models that reflect their values, interests, and analytical needs. The U.S. Army Corps of Engineers has developed this type of boundary process in their "shared vision planning."[20] A comprehensive website provides a history of the process, demonstrations and case studies, and tools and techniques for implementing the process.[21]

Recently, the International Joint Commission used the shared vision planning process in decisions about how to regulate water levels in both the Lake Ontario-St. Lawrence River system[22] and in the Upper Great Lakes.[23,24] Both studies engaged hundreds of participants from the United States and Canada in discussions about water level management options and the impacts of those options on ecosystems; recreational boating and tourism; hydropower; commercial navigation; municipal, industrial, and domestic water use; and the coastal zone. The models used in the studies incorporated information about ecosystem responses, shoreline dynamics, economics, and lake hydrology, and the potential operating plans were tested using multiple climate change scenarios. Although the shared vision planning process did not ultimately lead to consensus on a single recommended plan in the Lake Ontario-St. Lawrence River Study, the process did help improve participants' understanding of the system and develop a shared vision of possible futures.[22,25] Building on lessons from the Lake Ontario-St. Lawrence River Study, the Upper Great Lakes Study's use of shared vision planning did result in a single recommended plan.[24]

Using a Decision-Making Framework

The term "adaptive management" is used here to refer to a specific approach in which decisions are adjusted over time to reflect new scientific information and decision-makers learn from experience. The National Research Council (NRC) contrasts the processes of "adaptive management" and "deliberation with analysis."[3] Both can be used as part of an "iterative adaptive risk management framework" that is useful for decisions about adaptation and ways to reduce future climate change, especially given uncertainties and ongoing advances in scientific understanding.[8,26] Iterative adaptive risk management emphasizes learning by doing and continued adaptation to improve outcomes. It is especially useful when the likelihood of potential outcomes is very uncertain.

An idealized iterative adaptive risk management process includes clearly defining the issue, establishing decision criteria, identifying and incorporating relevant information, evaluating options, and monitoring and revisiting effectiveness (Figure 26.3). The process can be used in situations of varying complexity, and while it can be more difficult for complex decisions,[27] the incorporation of an iterative approach makes it possible to adjust decisions as information improves. Iterative adaptive risk management can be undertaken through collaborative processes that facilitate incorporation of stakeholder values in goal-setting and review of decision options.[28] Examples of the process and decision support tools that are helpful at its different stages are included in subsequent sections of this chapter.

Decision-Making Framework

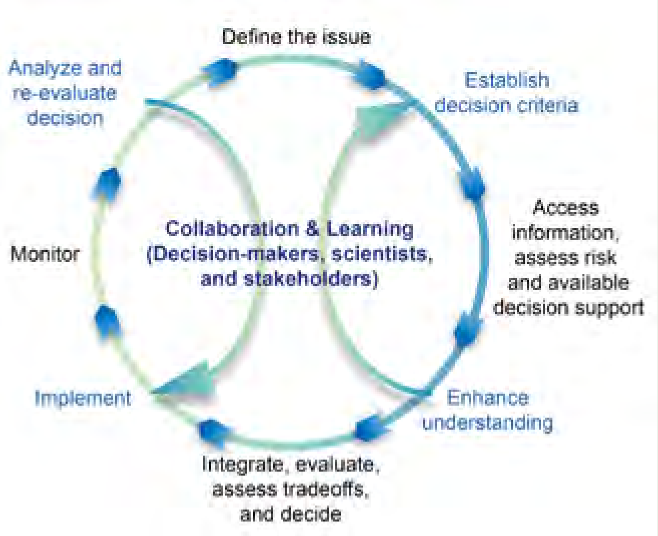


Figure 26.3. This illustration highlights several stages of a well-structured decision-making process. (Figure source: adapted from NRC 2010[8] and Willows and Connell 2003[26]).

Defining the Issue and Establishing Decision Criteria

An initial step in a well-structured decision process is to identify the context of the decision and factors that will affect choices – making sure that the questions are posed properly from scientific, decision-maker, and stakeholder (or public) perspectives (corresponding to the first two steps in Figure 26.3). An important challenge is identifying the stakeholders and how to engage them in decision-making processes. There are often many categories of stakeholders, including those directly and indirectly affected by, or interested in, the outcomes of decisions, as well as the decision-makers, scientists, and elected officials.[29] Other important considerations often overlooked but critical to defining the issue are:

- understanding the goals and values of the participants in the decision process;
- identifying risk perceptions and the sense of urgency of the parties involved in the decision;
- being clear about the time frame of the decision (short- versus long-term options relative to current and future risk levels) – and when the decision must be reached;
- acknowledging the scale and degree of controversy associated with the risks and opportunities as well as the alternatives;
- assessing the distribution of benefits or losses associated with current conditions and the alternatives being considered;
- reaching out to communities that will be affected but may lack ready access to the process (for example, considering environmental justice issues);
- recognizing the diverse interests of the participants;
- recognizing when neutral facilitators or trained science translators are needed to support the process; and
- understanding legal or institutional constraints on options.

Identifying and agreeing on decision criteria – metrics that help participants judge the outcomes of different decision options – can be extremely helpful in clarifying the basis for reaching a decision. Based on the relevant objectives, decision criteria can be established that reflect constraints and values of decision-makers and affected parties. Criteria can be quantitative (for example, obtaining a particular rate of return on investment) or qualitative (for example, maintaining a community's character or culture). If the issue identified is to reduce the risks associated with climate change, decision criteria might include minimizing long-term costs and maximizing public safety. Related sections below provide information on tools for valuing and comparing options and outcomes and provide a basis for using decision criteria.

Decision framing and establishment of decision criteria can be facilitated using various methods, including brainstorming, community meetings, focus groups, surveys, and problem mapping;[3,29] selecting among techniques requires consideration of a number of context-specific issues.[30] There are a variety of techniques for organizing, weighting information, and making tradeoffs for the goals that are important for a decision,[31,32] several of which are discussed in more detail in the section "Examples of Decision Support Tools and Methods."

Accessing Information

Developing a solid base of information to support decision-making is ideally a process of matching user needs with available information, including observations, models, and decision support tools. In some cases, needed information does not exist in the form useful to decision makers, thus requiring the capacity for synthesis of currently available information into new data products and formats. For decisions in the context of climate change and variability, it is critical to consult information that helps clarify the risks and opportunities to allow for appropriate planning and management. An example of information systems that synthesize data and products to support mitigation and adaptation decisions is the National Integrated Drought Information System (NIDIS), a federal, interagency effort to supply information about drought impacts and risks as well as decision support tools to allow sectors and communities to prepare for the effects of drought.[33] Learning from the successes of such efforts, the National Climate Assessment (NCA) is currently developing an indicator system to track climate changes as well as physical, natural, and societal impacts, vulnerabilities, and responses.[34] This effort is building on existing indicator efforts, such as the U.S. Environmental Protection Agency's (EPA) Climate Change Indicators,[35] NASA Vital Signs,[36] and NOAA indicator products,[37] as well as identifying when new data, information, and indicator products are needed.

Information technology systems and data analytics can harness vast data sources, facilitating collection, storage, access, analysis, visualization, and collaboration by scientists, analysts, and decision-makers. Such technologies allow for rapid scenario building and testing using many different variables, enhancing capacity to measure the physical impacts of climate change. These technologies are managing an increasing volume of data from satellite instruments, in situ (direct) measurement networks, and increasingly detailed and high-resolution models.[38] "Information Technology Supports Adaptation Decision-Making" below highlights use of an open platform data system that facilitated collaboration across multiple public and private sector entities in analyzing climate risk and adaptation economics along the U.S. Gulf Coast.

While progress is being made in development of data management and information systems, multiple challenges remain. Specific issues highlighted in the recent USGCRP *National Global Change Research Plan*[38] include data permanence, volume, transparency, quality control, and access. For data on socioeconomic systems – important for evaluating vulnerabilities, adaptation, and mitigation – privacy, confidentiality, and integration with broader systems of environmental data are important issues.[38] Experience with adaptation and mitigation decisions is often an excellent source of information and knowledge but is difficult to access and validate. Several organizations have been developing knowledge management systems for integrating this highly dispersed information and providing it to a network of practitioners (for example, CAKE 2012[39]). Addressing these and other challenges is essential for making progress in establishing a sustained assessment process and meeting the challenge of informing decision-making.[40]

INFORMATION TECHNOLOGY SUPPORTS ADAPTATION DECISION-MAKING

Entergy (a regional electric utility), Swiss Re (a reinsurance company), and the Economics of Climate Adaptation Working Group (a partnership between several public and private organizations) integrated natural catastrophe weather models with economic data to develop damage estimates related to climate change adaptation.[41] An extension of this work is the first comprehensive analysis of climate risks and adaptation economics along the U.S. Gulf Coast.[42] Another example is a simplified model, developed with support from EPA, to look at flooding risks associated with coastal exposure in southern Maine.[43] Use of an "open platform" system that allows multiple users to input and access data resulted in spreadsheets, graphs, and three-dimensional imagery displayed on contour maps downscaled to the city and county level for local decision-makers to access.[44]

Assessing, Perceiving, and Managing Risk

Making effective climate-related decisions requires balance among actions intended to manage, reduce, and transfer risk. Risks are threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences). As noted by the Intergovernmental Panel on Climate Change,[45] human choices affect the risks associated with climate variability and change. Such choices include how to manage our ecosystems and agriculture, where to live, and how to build resilient infrastructure. Choices regarding a portfolio of actions to address the risks associated with climate variability and change are most effective when they take into consideration the range of factors affecting human behavior, including people's perception of risk, the relative importance of those risks, and the socioeconomic context.[45,46] The process shown in Figure 26.4 is designed to help take such factors into consideration.

The next few sections describe the "integrate, evaluate, and decide" steps in Figure 26.3, which aim to help decision-makers choose *risk management* strategies. While a full quantitative risk analysis is not always possible, the concept of *risk assessment* coupled with understanding of *risk perception* provides a powerful framework for decision-makers to evaluate alternative options for managing the risks that they face today and in the future.[47] As described below, methods such as multiple criteria analysis, valuation of both risks and opportunities, and scenarios can help to combine experts' assessment of climate change risks with public perception of these risks, both influenced by the diverse values people bring to these questions[48] and in support of risk management strategies more likely to achieve both public support and their desired objectives.[46] To illustrate how this framework can be applied to resource management decisions, we use an example of coastal risk management decisions in the context of climate change.[49]

Linking Risk Assessment and Risk Perception with Risk Management of Climate Change

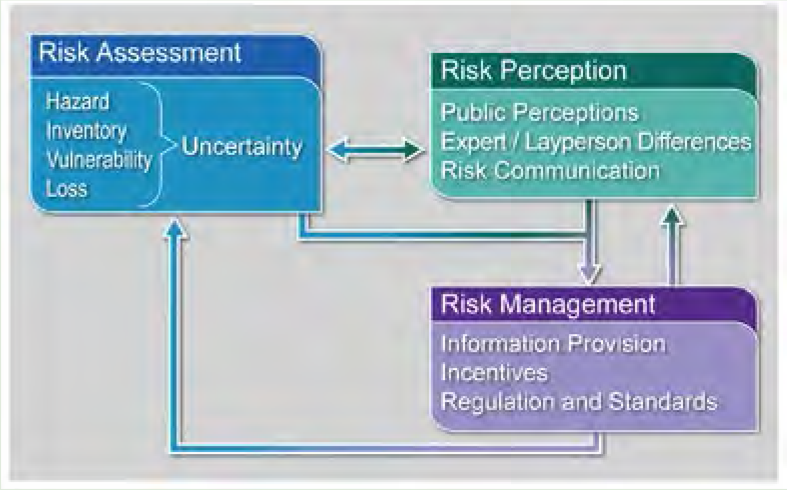


Figure 26.4. This figure highlights the importance of incorporating both experts' *assessment* of the climate change risk and general public *perceptions* of this risk in developing risk management strategies for reducing the negative impacts of climate change. As indicated by the arrows, how the public perceives risk should be considered when experts communicate data on the risks associated with climate change so the public refines its understanding of these risks. As the arrows indicate, the general public's views must also be considered in addition to experts' judgments when developing risk management strategies that achieve decision-makers' desired objectives. Climate change policies that are implemented will, in turn, affect both expert assessment and public perception of this risk in the future, as indicated by the feedback loop from risk management to these two boxes.

Risk Assessment

Risk assessment includes studies that estimate the likelihood of specific sets of events occurring and/or their potential consequences.[50] Experts often provide quantitative information regarding the nature of the climate change risk and the degree of uncertainty surrounding their estimates. Risk assessment focuses on the likelihood of negative consequences but does not exclude the possibility that there may also be beneficial consequences.

There are four basic elements for assessing risk – hazard, inventory, vulnerability, and loss.[51] This generalized approach to risk assessment is useful for a variety of types of decisions. The first element focuses on the risk of a *hazard* as a function of climate change, including interactions of climate effects with other factors. In the context of the coastal community example, the community is concerned with the likelihood of future hurricanes and the impacts that sea level rise may have on damage to the residential development from future hurricanes. There is likely to be considerable uncertainty about maximum storm surge and sea level from hurricanes during the next 50 to 70 years. The second element identifies the *inventory* of properties, people, and the environment at risk. To inventory structures, for instance, requires evaluating their location, physical dimensions, and construction quality.

Evaluating both the hazard and its impacts on the inventory often requires an appropriate treatment of uncertainty. In some cases a probabilistic treatment may prove sufficient. For instance, in the coastal community example, decision-makers may have sufficient confidence in estimates of the return frequency of extreme storms (for example, that the once-in-a-hundred-years storm is and will remain a once-in-a-hundred-years storm) to base their choices largely on these estimates. If such probabilistic estimates are not available, or if decision-makers lack sufficient confidence in those that are available, they may find it useful to consider a range of scenarios and seek risk management strategies robust across these ranges of estimates.[49,52,53]

Together, the hazard and inventory elements enable calculation of the damage *vulnerability* of the structures, people, and environment at risk. The vulnerability component enables estimation of the human, property, and environmental *losses* from different climate change scenarios by integrating biophysical information on climate change and other stressors with socioeconomic and environmental information.[54] These assessments typically involve evaluation of exposure, sensitivity, and adaptive capacity for current and projected conditions. Quantitative indicators are increasingly used to diagnose potential vulnerabilities under different scenarios of socioeconomic and environmental change[55] and to identify priorities and readiness for adaptation investments.[56] In the case of a coastal residential development, the design of the facility will influence its ability to reduce damage from hurricanes and injuries or fatalities from hurricane storm surge and sea level rise. Decisions may involve determining whether to elevate the facility so it is above ten feet, how much this adaptation measure will cost, and the reduction in the impact of future hurricanes on damage to the facility and on the residents in the building, as a function of different climate change scenarios.

Risk Perception in Climate Change Decision-Making

The concept of risk perception refers to individual, group, and public views and attitudes toward risks, where risks are understood as threats to life, health and safety, the environment, economic well-being, and other things of value. Risk perception encompasses perspectives on various dimensions of risks, including their severity, scope, incidence, timing, controllability, and origins or causes. The knowledge base regarding risk perception includes research in psychology, social psychology, sociology, decision science, and health-related disciplines (see “Factors Affecting Attitudes Toward Risk”).

As noted in “Factors Affecting Attitudes Towards Risk,” many factors influence risk. Social scientists and psychologists have studied people’s concerns about climate change risks and found that many individuals view hazards for which they have little personal knowledge and experience as highly risky.[72] On the other hand, seeing climate change as a simple and gradual change from current to future values on variables such as average temperatures and precipitation may make it seem controllable.[73]

The effects of risk perception on decision-making have also been studied extensively and support a number of conclusions that need to be considered in decision support processes. The decision process of non-experts with respect to low-probability, high-consequence events differs from that of experts.[74] Non-experts tend to focus on short time horizons, seeking to recoup investments over a short period of time, in which case future impacts from climate change are not given much weight in actions taken today. This is a principal reason why there is a lack of interest in undertaking adaptation measures with upfront investments costs where the benefits accrue over

FACTORS AFFECTING ATTITUDES TOWARDS RISK

Extensive literature indicates that a range of factors shape risk perceptions. For example, psychological risk dimensions have been shown to influence people’s perceptions of health and safety risks across numerous studies in multiple countries.[57] People also often use common “mental shortcuts,” such as availability and representativeness, to organize a wide range of experiences and information.[58] How risks are framed is also important – for example, as numbers versus percentages and worst-case formulations versus more probable events.[59] Recent research has emphasized the role of emotions in the perception of risk.[60,61]

Other factors explored in the literature center on perceived characteristics of specific risks, such as whether the risks are familiar or unfamiliar; prosaic or perceived as catastrophic (“dread” risks); reversible or irreversible; and voluntarily assumed or imposed.[62] Risk perception is also influenced by the social characteristics of individuals and groups, including gender, race, and socioeconomic status.[61,63] Experiences with specific risks are also important, such as being affected by a hazard (for discussions, see Figner and Weber 2011;[64] NRC 2006;[64] Tierney et al. 2001[66]) and experiencing near misses or false alarms.[67]

Risk perceptions do not exist as isolated perceptions, but are linked to other individual and group perceptions and beliefs and to psychosocial factors, such as fatalism, locus of control (the degree to which people feel they have control over their own lives and outcomes), and religiosity,[65,66] as well as to more general worldviews. Research has also focused on people’s mental models regarding the causality and effects of different risks.[68]

Still other research focuses on how risk information is mediated through organizations and institutions and how mediation processes influence individual and group risk perceptions. For example, the “social amplification of risk” framework stresses the importance of the media and other institutions in shaping risk perceptions, such as by making risks seem more or less threatening.[69] Perceptions are also related to people’s trust in the institutions that manage risk; loss of trust can lead to feelings of disloyalty regarding organizations that produce risks and institutions charged with managing them, which can in turn amplify individual and public concerns.[70] Additionally, perceptions are linked to individual and group attitudes concerning sources of risk information, including official and media sources. These factors include the perceived legitimacy, credibility, believability, and consistency of information sources.[71]

a long period of time.[75] In the context of the coastal residential development, elevating the structure will reduce expected damages from hurricanes, resulting in smaller annual insurance premiums. Long-term loans that spread the costs of this action over time can make the option financially attractive, if the savings on the insurance premiums outweigh the costs of the loan payments.

There is also a tendency for decision-makers to treat a low-probability event as if it had no chance of occurring because it is below their threshold level of concern (such as a 1 in 100 chance of a damaging disaster occurring next year). As shown by empirical research, stretching the time horizon over which information is communicated can make a difference in risk perception.[76] In the case of the coastal residential development, community leaders may pay more attention to the need for adaptation measures if the likelihood of inundation by a future hurricane is presented over a 25-year or 50-year horizon (for example, the facility may flood 5 times in 25 years) rather than as a risk on annual basis (for example, there is a 20% chance of flooding in any given year).

Risk Management Strategies

In general, an effective response to the current and future risks from climate variability and change will require a portfolio of different types of actions, ranging from those intended to manage, reduce, and transfer risk to those intended to provide additional information on risks and the effectiveness of various actions for addressing it (see "Value of Information"). For instance, in the coastal community example, decision-makers might better *manage* risk through changes in building codes intended to reduce the impact of flooding on structures, might *share* risk by appropriate adjustments in flood insurance rates, and might *reduce* risk via land-use policies that shift development towards higher ground and via participating in and advocating for greenhouse gas emission reduction policies that may reduce future levels of sea level rise.

To facilitate these strategies given the uncertainty associated with the likelihood and consequences of climate change, "robust decision-making" may be a useful tool for evaluating alternative options and risk management strategies. One study reviews the application of a range of decision-making approaches to assessing options for mitigating or adapting to the impacts of climate change.[77] In the context of the coastal residential development, the choice of adaptation measures to reduce the likelihood of future water-related damage may require using such an approach. To illustrate, consider two adaptation measures, elevating a building and flood-proofing it, to reduce the chances of severe water damage from hurricane storm surge coupled with sea level rise. Measure 1 (elevation) may perform extremely well based on specific estimates of the likelihood of different climate change conditions that will affect storm surge and sea level rise, but it may perform poorly if those estimates turn out to be mistaken. Measure 2 (flood-proofing) may have a lower expected benefit than elevation but much less variance in its outcomes and thus be the preferred choice of the community.[49]

Turning to risk management strategies, public agencies, private firms, and individuals have incentives, information, and options available to adapt to emerging conditions due to climate change. These options may include ensuring continuity of service or fulfillment of agency responsibilities, addressing procurement or supply chain issues, preserving market share, or holding the line on agency or private-sector production costs. Commercially available mechanisms such as insurance can also play a role in providing protection against losses due to climate change.[78] However, insurers may be unwilling to provide coverage against such losses due to the uncertainty of the risks and lack of clarity on the liability issues associated with global climate change.[79] In these cases, public sector involvement through public education programs, economic incentives (subsidies and fines), and regulations and standards may be relevant options. Criteria for evaluating risk management strategies can include impacts on resource allocation, equity and distributional impacts, ease of implementation, and justification.

VALUE OF INFORMATION

A frequently asked question when making complex decisions is: "When does the addition of more information contribute to decision-making so that the benefit of obtaining this information exceeds the expense of collecting, processing, or waiting for it?" In a decision context, the value of information often is defined as the expected additional benefit from additional information, relative to what could be expected without that information.[80,81] Even though decision-makers often cite a lack of information as a rationale for not making timely decisions, delaying a decision to obtain more information does not always lead to different or better decisions.[82,83]

Implementation, Continued Monitoring, and Evaluation of Decisions

The implementation phase of a well-structured decision process involves an ongoing cycle of setting goals, taking action, learning from experience, and monitoring to evaluate the consequences of undertaking specific actions, as shown on the left-hand side of Figure 26.3. This cycle offers the potential for policy and outcome improvement through time. Ongoing evaluation can focus on how the system responds to the decision, leading to better future decisions, as well as on how different stakeholders respond, resulting in improvements in future decision-making processes. The need for social and technical learning to inform decision-making is likely to increase in the face of pressures on social and resource systems from climate change. However, the relative effectiveness of monitoring and assessment in producing social and technical learning depends on the nature of the problem, the amount and kind of uncertainty and risk associated with climate change, and the design of the monitoring and evaluation efforts.

Examples of Decision Support Tools and Methods

While decision frameworks vary in their details, they generally incorporate most or all of the steps outlined above. To support decision-making across these steps, various technical tools and methods, developed in both the public and private sectors, can assist stakeholders and decision-makers in meeting their objectives and clarify where there are value differences or varying tolerances for risk and uncertainty. Many of these tools and methods are applicable throughout the decision-making process, from framing through assessment of options through evaluation of outcomes. Several of the tools and methods – data management systems and scientific assessments – help to expand the relevant information and provide a means of managing large amounts of data. Three other tools described below – comparative tradeoff methods, scenario planning, and integrated assessment models – are particularly useful in assisting stakeholders and decision-makers in identifying and evaluating different options for managing risks associated with climate change. The following discussion describes these approaches; examples are provided in “Example Decision Support Tools.”

EXAMPLE DECISION SUPPORT TOOLS

Many decision support tools apply climate science and other information to specific decisions and issues; several online clearinghouses describe these tools and provide case studies of their use (for example, CAKE 2012;[39] CCSP 2005;[84] NatureServe 2012[85]). Typically, these applications integrate observed or modeled data on climate and a resource or system to enable users to evaluate the potential consequences of options for management, investment, and other decisions. These tools apply to many types of decisions; examples of decisions and references for further information are provided in Table 26.2.

Table 26.2. Examples of Decisions and Tools Used

Topic	Example Decision(s)	Further Information and Case Studies
Water resources	Making water supply decisions in the context of changes in precipitation, increased temperatures, and changes in water quality, quantity, and water use	Means et al. 2010;[86] International Upper Great Lakes Study 2012;[24] State of Washington 2012;[87] “Denver Water Case Study” (below); Ch. 3: Water
Infrastructure	Designing and locating energy or transportation facilities in the coastal zone to limit the impacts of sea level rise	Ch. 11: Urban; Ch. 10: Energy, Water, and Land
Ecosystems and biodiversity	Managing carbon capture and storage, fire, invasive species, ecosystems, and ecosystem services	Byrd et al. 2011;[88] Labiosa et al. 2009;[89] USGS 2012a, 2012b, 2012c;[90,91] Figure 26.5
Human health	Providing public health warnings in response to ecosystem changes or degradation, air quality, or temperature issues	Ch. 9: Human Health
Regional climate change response planning	Develop plans to reduce emissions of greenhouse gases in multiple economic sectors within a state	“Washington State’s Climate Action Team” (below)

Continued

EXAMPLE DECISION SUPPORT TOOLS (CONTINUED)

Many available and widely applied decision-making tools can be used to support management in response to climate extremes or seasonal fluctuations. Development of decision support resources focused on decadal or multi-decadal investment decisions is in a relatively early stage but is evolving rapidly and shared through the types of clearinghouses discussed above.

Land-use Planning Tool for the Upper Santa Cruz Watershed

▼ General Data

☐ Binational Features

☑ Hydrology

☑ Santa Cruz Watershed

☐ Population Density

▼ SWAT Results

○ None

● 85606 Evapotranspiration

○ 85606 Percolation

○ 85606 Sediment Yield

○ 85606 Surface Runoff

▼ Land Use/Land Cover

○ Existing ○ Future ● None

▼ Base Imagery

○ None

○ The National Map

○ The National Map Imagery

Figure 26.5. The Santa Cruz Watershed Ecosystem Portfolio Model is a regional land-use planning tool that integrates ecological, economic, and social information and values relevant to decision-makers and stakeholders. The tool is a map-based set of evaluation tools for planners and stakeholders, and is meant to help in balancing disparate interests within a regional context. Projections for climate change can be added to tools such as this one and used to simulate impacts of climate change and generate scenarios of climate change sensitivity; such an application is under development for this tool (Figure source: USGS 2012[90]).

Valuing the Effects of Different Decisions

Understanding costs and benefits of different decisions requires understanding people's preferences and developing ways to measure outcomes of those decisions relative to preferences. This "valuation" process is used to help rank alternative actions, illuminate tradeoffs, and enlighten public discourse.[31] In the context of climate change, the process of measuring the economic values or non-monetary benefits of different outcomes involves managers, scientists, and stakeholders and a set of methods to help decision-makers evaluate the consequences of climate change decisions.[92] Although values are defined differently by different individuals and groups and can involve different metrics – for example, monetary values and non-monetary benefit measures[93] – in all cases, valuation is used to assess the relative importance to the public or specific stakeholders of different impacts. Such valuation assessments can be used as inputs into iterative adaptive risk management assessments (which has advantages in a climate context because of its ability to address uncertainty) or more traditional cost-benefit analyses, if appropriate.

Some impacts ultimately are reflected in changes in the value of activities within the marketplace and in dollars[94] – for example, the impacts of increased temperatures on commercial crop yields.[95] Other evaluations use non-monetary benefit measures such as biodiversity measures[96] or soil conservation and water services.[97]

Valuation methods can provide input to a range of decisions, including cost-benefit analysis of new or existing regulations[98] or government projects;[99] assessing the implications of land-use changes;[100] transportation investments and other planning efforts;[101,102] developing metrics for ecosystem services; and stakeholder and conflict resolution processes.[103]

Comparative Tradeoff Methods

Once their consequences are valued or otherwise described, alternative options are often compared against the objectives or decision criteria. In such cases, approaches such as listing the pros and cons,[104] cost-benefit analysis,[105] multi-criteria methods,[80] or robust decision methods[106] can be useful. Multi-criteria methods provide a way to compare options by considering the positive and negative consequences for each of the objectives without having to choose a single valuation method for all the attributes important to decision-makers.[31] This approach allows for consequences to be evaluated using criteria most relevant for a given objective.[107] The options can then be compared directly by considering the relative importance of each objective for the particular decision.

Integrated Assessment Models

Integrated Assessment Models are tools for modeling interactions across climate, environmental, and socioeconomic systems.[108] In particular, integrated assessment models can be used to provide information that informs tradeoffs analyses, often by simulating the potential consequences of alternative decisions. Integrated assessment models typically include representations of climate, economics, energy, and other technology systems, as well as demographic trends and other factors that can be used in scenario development and uncertainty quantification.[109] They are useful in national and global policy decisions about emissions targets, timetables, and the implications of different technologies for emissions management.[110] These models are now being extended to additional domains such as water resources and ecosystem services to inform a broader range of tradeoff analyses and to finer resolutions to support regional decision-making.[111]

Scenarios and Scenario Planning

Scenarios are depictions of possible futures or plausible conditions given a set of assumptions; they are not predictions. Scenarios enable decision makers to consider uncertainties in future conditions and explore how alternate decisions could shape the futures or perform under uncertainty. One approach to building scenarios begins with identifying any changes over time that might occur in climate and socioeconomic factors (for example, population growth and changes in water availability), and then using these projections to help decision-makers rank the desirability of alternative decision options to respond to these changes.[112] This works well when decision-makers agree on the definition of the problem and scientific evidence.[53,113] A second approach is widely used in robust decision-making and decision-scaling approaches. It begins with a specific decision under consideration by a specific community of users and then poses questions relevant to these decisions (for example, “how can we build a vibrant economy in our community in light of uncertainty about population growth and water supply?”) to organize information about future climate and socioeconomic conditions (for example, Robinson 1988[114]).

Scenario planning often combines quantitative science-based scenarios with participatory “visioning” processes used by communities and organizations to explore desired futures.[115] It can also facilitate participatory learning and development of a common understanding of problems or decisions. There are many different approaches, from a single workshop that uses primarily qualitative approaches to more complex exercises that integrate qualitative and quantitative methods with visualization and/or simulation techniques over multiple workshops or meetings. Common elements include scoping and problem definition; group development of qualitative (and, optionally, quantitative) scenarios and analyses that explore interactions of key driving forces, uncertainties, and decision options.

Scenario planning has been useful for water managers such as Denver Water, which has also used “robust decision-making” to assess policies that perform well across a wide range of future conditions, in the face of uncertainty and unknown probabilities (see “Denver Water Case Study”). Other examples of the use of scenario planning include:

- National Park Service, to consider potential climate change impacts and identify adaptation needs and priorities in several parks or regions[116]
- California State Coastal Conservancy, to plan tidal marsh restoration and planning in the San Francisco estuary in the face of climate change and sea level rise[117]
- Urban Ecology Research Lab at the University of Washington, for planning adaptation to preserve ecosystem services in the Snohomish Basin[118]
- A group of agencies and organizations considering the impacts of climate change on ecosystems in the Florida Everglades[119]

The National Climate Assessment has developed and used a number of different types of scenarios and approaches in preparation of this report (see Appendix 5: Scenarios and models).[120]


NOAA/NCDC

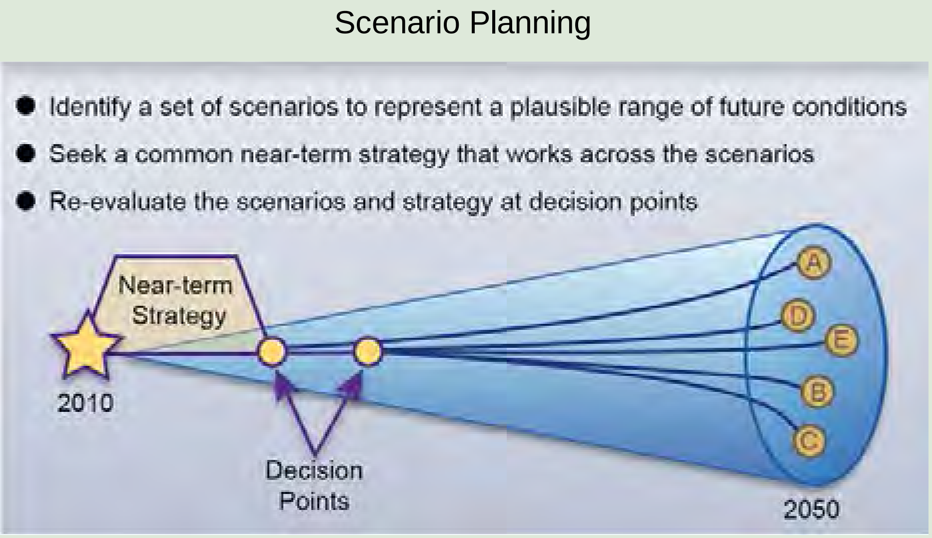
DENVER WATER CASE STUDY


©Denver Water

Climate change is one of the biggest challenges facing the Denver Water system. Due to recent and anticipated effects of climate variability and change on water availability, Denver Water faces the challenge of weighing alternative response strategies and is looking at developing options to help meet more challenging future conditions.

Denver Water is using scenario planning in its long-range planning process (looking out to 2050) to consider a range of plausible future scenarios (Figure 26.6). This approach contrasts with its traditional approach of planning for a single future based on demand projections and should better prepare the utility and enhance its ability to adapt to changing and uncertain future conditions.

Denver Water is assessing multiple scenarios based on several potential water system challenges, including climate change, demographic and water-use changes, and economic and regulatory changes. The scenario planning strategy includes "robust decision-making," which focuses on keeping as many future options open as possible while trying to ensure reliability of current supplies.



- Identify a set of scenarios to represent a plausible range of future conditions
- Seek a common near-term strategy that works across the scenarios
- Re-evaluate the scenarios and strategy at decision points

Figure 26.6: Scenario planning is an important component of decision-making. This "cone of uncertainty" is used to depict potential futures in Denver Water's scenario planning exercises. (Figure source: adapted from Waage 2010[122]).

Scenario planning was chosen as a way to plan for multiple possible futures, given the degree of uncertainty associated with many variables, particularly demographic change and potential changes in precipitation. This method is easy to understand and has gained acceptance across the utility. It is a good complement to more technical, detailed analytical approaches.

The next step for Denver Water is to explore a more technical approach to test their existing plan and identified options against multiple climate change scenarios. Following a modified robust decision-making approach,[121] Denver Water will test and hedge its plan and options until those options demonstrate that they can sufficiently handle a range of projected climate conditions.

Scientific Assessments

Ongoing assessments of the state of knowledge allow for iterative improvements in understanding over time and can provide opportunities to work directly with decision-makers to understand their needs for information.[123] A sustained assessment process (Ch. 30: Sustained Assessment)[40] can be designed to support the adaptation and mitigation information needs of decision-makers, with ongoing improvements in data quality and utility over time. This report represents one such type of assessment. The Intergovernmental Panel on Climate Change (IPCC) has prepared assessments of the state of the science related to climate change, impacts and adaptation, and mitigation since the late 1980s. Numerous additional assessments have been prepared for a variety of national and international bodies focused on issues such as biodiversity, ecosystem services, global change impacts in the Arctic, and many others.

WASHINGTON STATE'S CLIMATE ACTION TEAM: USES AND LIMITS TO DECISION SUPPORT

Between 2000 and 2007, pioneering work by the University of Washington's Climate Impacts Group (a NOAA RISA) tailored national climate models to the Pacific Northwest and produced, for the first time, specific information about likely adverse impacts to virtually every part of Washington's economy and environment if carbon dioxide concentrations in the atmosphere were not quickly stabilized.[124] The localized impacts predicted from these models were significant.

In February of 2007, Governor Christine Gregoire issued Executive Order 07-02, establishing the Climate Action Team (CAT).[125] Its charge was to develop a plan to achieve dramatic, climate-stabilizing reductions in emissions of greenhouse gases according to goals established in the Executive Order. The CAT was a 29-member team that included representatives of industry, utilities, environmental advocacy groups, Native American tribes, state and municipal governments, and elected officials.

The CAT met four to five times a year for two years. Between meetings, technical consultants, including boundary organizations such as the Climate Impacts Group, provided detailed analyses of the issues that were on the next CAT agenda. Technical experts were recruited to provide direct testimony to the CAT. Professional facilitators helped run the meetings, decipher the technical testimony, and keep the CAT on track to meet its obligations. All CAT meetings were open to the public, and public testimony was accepted. To assist in this effort, five subcommittees were created to develop proposals for achieving emissions reductions in the following parts of the economy: the built environment, agriculture, forestry, transportation, and energy generation. Similarly, adaptation groups were formed to develop recommendations for dealing with impacts that could not be avoided. These Preparation/Adaptation Working Groups focused on forest health, farmlands, human health, and coastal infrastructure and resources.

The CAT and the working groups were well supported with science and technical expertise. The CAT issued its first report, on reducing greenhouse gases, at the close of 2007.[126] It was well received by the legislature, and a significant number of its recommendations were implemented in the 2008 session.[127]

In 2008, the CAT continued its work. The focus shifted to whether Washington should join the Western Climate Initiative (WCI), a state and provincial organization that was developing a regional, economy-wide cap and trade system for carbon emissions. The same high-quality professional facilitation was provided at all meetings. Several highly qualified technical experts provided technical support.

With this support, the CAT produced another set of recommendations.[128] The centerpiece recommendation was that Washington join the WCI's regional cap and trade program. This time, the combination of a weakening economy and political dynamics trumped the CAT's findings, and resulted in a decision not to implement its recommendations.

Incorporating Recent Scientific Advances and Translating Science for Decision-Making

While decision support is not necessarily constrained by a lack of tools, a number of barriers restrict application of existing and emerging science and technology in adaptation and mitigation decisions.[3,8,129] In cases where tools exist, decision-makers may be 1) unaware of tools; 2) overwhelmed by the number of tools; 3) hesitant to use tools that are not appraised or updated and maintained with new information; or 4) require training in how to use tools.[8,130] Recent scientific developments could help address some of these barriers, but are not yet incorporated into decision support tools.[65] For example, individual climate models can provide very different projections of future climate conditions for a given region, and the divergence of these projections can make it seem impossible to reach a decision. But comparing different models and constructing climate model "ensembles" can highlight areas of agreement across large numbers of models and model runs, and can also be used to develop ranges and other forms of quantification of uncertainty (for further discussion, see Ch. 2: Our Changing Climate and Appendix 3: Climate Science Supplement). While results from these activities can prove difficult to present in formats that could help decision-makers,[131] new approaches to visualization and decision support can make such ensembles useful for decision-making.[132]

There is also a need for "science translators" who can help decision-makers efficiently access and properly use data and tools that would be helpful in making more informed decisions in the context of climate change.[3,4,8,83,133] The culture of research in the United States often perpetuates a belief that basic and applied research need to be kept separate, though it has been demonstrated that research motivated by "considerations of use" can also make fundamental advances in scientific understanding and theory.[134] The U.S. climate research effort has been strongly encouraged to improve integration of social and ecological sciences and to develop the capacity for decision support to help address the need to effectively incorporate advances in climate science into decision-making.[135]

Research to Improve Decision Support

There are a number of areas where scientific knowledge needs to be expanded or tools further developed to take advantage of existing insight. The National Research Council (NRC) identifies a research agenda both *for* decision support (such as identifying specific information needs) and *on* decision support (such as improving tools for risk assessment and management).[3] A number of studies assess approaches and identify needed research and development (for example, Arvai et al. 2006[136]). A subset of the opportunities and needs identified by the NRC seem particularly relevant in the context of the National Climate Assessment, including:

- A comprehensive analysis of the state of decision support for adaptation and mitigation, including assessment of processes, tools, and applications, and development of a knowledge-sharing platform will facilitate wide public access to these resources.
- Comparisons of different adaptation and mitigation options will be improved by investments in understanding how the effects of climate change and response options can be valued and compared, especially for non-market ecosystem goods and services[101,137] and those impacts and decisions that have an effect over long time scales.
- Improvements in risk management require closing the gap between expert and public understanding of risk and building the institutions and processes needed for managing persistent risks over the long term.
- Probabilistic forecasts or other information regarding consequential climate extremes/events have the potential to be very useful for decision-makers, if used with improving information on the consequences of climate change and appropriate decision support tools.
- Better methods for assessing and communicating scientific confidence and uncertainty in the context of specific decisions would be very useful in supporting risk management strategies.
- Improvements in processes that effectively link scientists with decision-makers and the public in resource management settings and developing criteria to evaluate their effectiveness would enhance knowledge building and understanding.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

During March-June 2012, the author team engaged in multiple technical discussions via teleconference (6 telecons) and email and in a day-long in-person meeting (April 27, 2012, in Washington, D.C.). Authors reviewed over 50 technical inputs provided by the public and a wide variety of technical and scholarly literature related to decision support, including reports from the National Research Council that provided recent syntheses of the field (America's Climate Choices series, especially the reports *Informing an Effective Response to Climate Change*[8] and *Informing Decisions in a Changing Climate*[3]). During the in-person meeting, authors reflected on the body of work informing the chapter and drafted a number of candidate critical messages that could be derived from the literature. Following the meeting, authors ranked these messages and engaged in expert deliberation via teleconference and email discussions in order to agree on a small number of key messages for the chapter.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Decisions about how to address climate change can be complex, and responses will require a combination of adaptation and mitigation actions. Decision-makers – whether individuals, public officials, or others – may need help integrating scientific information into adaptation and mitigation decisions.

Description of evidence base

The sensitivity of the climate system to human activities, the extent to which mitigation policies are implemented, and the effects of other demographic, social, ecological, and economic changes on vulnerability also contribute to uncertainty in decision-making.

Uncertainties can make decision-making in the context of climate change especially challenging for several reasons, including the rapid pace of changes in physical and human systems, the lags between climate change and observed effects, the high economic and political stakes, the number and diversity of potentially affected stakeholders, the need to incorporate scientific information of varying confidence levels, and the values of stakeholders and decision-makers.[2,3]

An iterative decision process that incorporates constantly improving scientific information and learning through periodic reviews of decisions over time is helpful in the context of rapid changes in environmental conditions.[3,4] The National Research Council has concluded that an "iterative adaptive risk management" framework, in which decisions are adjusted over time to reflect new scientific information and decision-makers learn from experience, is appropriate for decisions about adaptation and ways to reduce future climate change, especially given uncertainties and advances in scientific understanding.[8,26]

Well-designed decision support processes, especially those in which there is a good match between the availability of scientific information and the capacity to use it, can result in more effective outcomes based on relevant information that is perceived as useful and applicable.[6]

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

N/A

KEY MESSAGE #2 TRACEABLE ACCOUNT

To be effective, decision support processes need to take account of the values and goals of the key stakeholders, evolving scientific information, and the perceptions of risk.

Description of evidence base

This message emphasizes that making a decision is more than picking the right tool and adopting its outcome. It is a process that should involve stakeholders, managers, and decision-makers to articulate and frame the decision, develop options, consider consequences (positive and negative), evaluate tradeoffs, make a decision, implement, evaluate, learn, and reassess.[1,8] Oftentimes having an inclusive, transparent decision process increases buy-in, regardless of whether a particular stakeholder's preferred option is chosen.[3] Decisions about investment in adaptation and mitigation measures occur in the context of uncertainty and high political and economic stakes, complicating the evaluation of information and its application in decision-making.[3,8] Decisions involve both scientific information and values – for example, how much risk is acceptable and what priorities and preferences are addressed.[2]

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

KEY MESSAGE #3 TRACEABLE ACCOUNT

Many decision support processes and tools are available. They can enable decision-makers to identify and assess response options, apply complex and uncertain information, clarify tradeoffs, strengthen transparency, and generate information on the costs and benefits of different choices.

Description of evidence base

Many decision support tools have been developed to support adaptive management in specific sectors or for specific issues. These tools include: risk assessments; geographic information system (GIS)-based analysis products; targeted projections for high-consequence events such as fires, floods, or droughts; vulnerability assessments; integrated assessment models; decision calendars; scenarios and scenario planning; and others.[3,8,84] Many of these tools have been validated scientifically and evaluated from the perspective of users. They are described in the sector and regional chapters of this assessment. In addition, a variety of clearing houses and data management systems provide access to decision support information and tools (for example, CAKE 2012; NatureServe 2012[39,85]).

There are many tools, some of which we discuss in the chapter, that are currently being used to make decisions that include a consideration of climate change and variability, or the impacts or vulnerabilities that would result from such changes.

Also important is the creation of a well-structured and transparent decision process that involves affected parties in problem framing, establishing decision criteria, fact finding, deliberation, and reaching conclusions.[1,8,26] These aspects of decision-making are often overlooked by those who focus more on scientific inputs and tools, but given the high stakes and remaining uncertainties, they are crucial for effective decision-making on adaptation and mitigation.

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

KEY MESSAGE #4 TRACEABLE ACCOUNT

Ongoing assessment processes should incorporate evaluation of decision support tools, their accessibility to decision-makers, and their application in decision processes in different sectors and regions.

Description of evidence base

As part of a sustained assessment, it is critical to understand the state of decision support, including what is done well and where we need to improve. At this point in time, there is a lack of literature that provides a robust evidence base to allow us to conduct this type of national, sector-scale assessment. Developing an evidence base would allow for a movement from case studies to larger-scale assessment across decision support and would allow us to better understand how to better utilize what decision support is available and understand what needs to be improved to support adaptation and mitigation decisions in different sectors and regions.

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

KEY MESSAGE #5 TRACEABLE ACCOUNT

Steps to improve collaborative decision processes include developing new decision support tools and building human capacity to bridge science and decision-making.

Description of evidence base

There are many challenges in communicating complex scientific information to decision makers and the public,[11] and while "translation" of complex information is one issue, there are many others. Defining the scope and scale of the relevant climate change problem can raise both scientific and social questions. These questions require both scientific insights and consideration of values and social constructs, and require that participants engage in mutual learning and the co-production of relevant knowledge.[10] Boundary processes that are collaborative and iterative[18] among scientists, stakeholders, and decision-makers, such as joint fact finding and collaborative adaptive management, foster ongoing dialogue and increasing participants' understanding of policy problems and information and analysis necessary to evaluate decision options.[12,13] Analysis of the conditions that contribute to their effectiveness of boundary processes is an emerging area of study.[13]

A large body of literature notes that the ability of decision-makers to use data and tools has not kept pace with the rate at which new tools are developed, pointing to a need for "science translators" who can help decision-makers efficiently access and properly use data and tools that would be helpful in making more informed decisions in the context of climate change.[3,4,8,83,133] The U.S. climate research effort has been strongly encouraged to improve integration of social and ecological sciences and to develop the capacity for decision support to help address the need to effectively incorporate advances in climate science into decision-making.[135]

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

Climate Change Impacts in the United States

CHAPTER 27
MITIGATION

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

27 MITIGATION

Key Messages

1. **Carbon dioxide is removed from the atmosphere by natural processes at a rate that is roughly half of the current rate of emissions from human activities. Therefore, mitigation efforts that only stabilize global emissions will not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase. The same is true for other long-lived greenhouse gases.**
2. **To meet the lower emissions scenario (B1) used in this assessment, global mitigation actions would need to limit global carbon dioxide emissions to a peak of around 44 billion tons per year within the next 25 years and decline thereafter. In 2011, global emissions were around 34 billion tons, and have been rising by about 0.9 billion tons per year for the past decade. Therefore, the world is on a path to exceed 44 billion tons per year within a decade.**
3. **Over recent decades, the U.S. economy has emitted a decreasing amount of carbon dioxide per dollar of gross domestic product. Between 2008 and 2012, there was also a decline in the total amount of carbon dioxide emitted annually from energy use in the United States as a result of a variety of factors, including changes in the economy, the development of new energy production technologies, and various government policies.**
4. **Carbon storage in land ecosystems, especially forests, has offset around 17% of annual U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" may not be sustainable.**
5. **Both voluntary activities and a variety of policies and measures that lower emissions are currently in place at federal, state, and local levels in the United States, even though there is no comprehensive national climate legislation. Over the remainder of this century, aggressive and sustained greenhouse gas emission reductions by the United States and by other nations would be needed to reduce global emissions to a level consistent with the lower scenario (B1) analyzed in this assessment.**

Mitigation refers to actions that reduce the human contribution to the planetary greenhouse effect. Mitigation actions include lowering emissions of greenhouse gases like carbon dioxide and methane, and particles like black carbon (soot) that have a warming effect. Increasing the net uptake of carbon dioxide through land-use change and forestry can make a contribution as well. As a whole, human activities result in higher global concentrations of greenhouse gases and to a warming of the planet – and the effect is increased by various self-reinforcing cycles in the Earth system (such as the way melting sea ice results in more dark ocean water, which absorbs more heat, and leads to more sea ice loss). Also, the absorption of increased carbon dioxide by the oceans is leading to increased ocean acidity with adverse effects on marine ecosystems.

Four mitigation-related topics are assessed in this chapter. First, it presents an overview of greenhouse gas emissions and their climate influence to provide a context for discussion of mitigation efforts. Second, the chapter provides a survey of activities contributing to U.S. emissions of carbon dioxide and other greenhouse gases. Third, it provides a summary of current government and voluntary efforts to manage these emissions. Finally, there is an assessment of the adequacy of these efforts relative to the magnitude of the climate change threat and a discussion of preparation for potential future action.

While the chapter presents a brief overview of mitigation issues, it does not provide a comprehensive discussion of policy options, nor does it attempt to review or analyze the range of technologies available to reduce emissions.

These topics have also been the subject of other assessments, including those by the National Academy of Sciences[1] and the U.S. Department of Energy.[2] Mitigation topics are addressed throughout this report (see Ch. 4: Energy, Key Message 5; Ch. 5: Transportation, Key Message 4; Ch. 7: Forests, Key Message 4; Ch. 9: Human Health, Key Message 4; Ch. 10: Energy, Water, and Land, Key Messages 1, 2, 3; Ch. 13: Land Use & Land Cover Change, Key Messages 2, 4; Ch. 15: Biogeochemical Cycles, Key Message 3; Ch. 26: Decision Support, Key Messages 1, 2, 3; Appendix 3: Climate Science Supplemental Message 5; Appendix 4: FAQs N, S, X, Y, Z).

Emissions, Concentrations, and Climate Forcing

Setting mitigation objectives requires knowledge of the Earth system processes that determine the relationship among emissions, atmospheric concentrations and, ultimately, climate. Human-caused climate change results mainly from the increasing atmospheric concentrations of greenhouse gases.[3] These gases cause radiative "forcing" – an imbalance of heat trapped by the atmosphere compared to an equilibrium state. Atmospheric concentrations of greenhouse gases are the result of the history of emissions and of processes that remove them from the atmosphere; for example, by "sinks" like growing forests.[4] The fraction of emissions that remains in the atmosphere, which is different for each greenhouse gas, also varies over time as a result of Earth system processes.

The impact of greenhouse gases depends partly on how long each one persists in the atmosphere.[5] Reactive gases like methane and nitrous oxide are destroyed chemically in the atmosphere, so the relationships between emissions and atmospheric concentrations are determined by the rate of those reactions. The term "lifetime" is often used to describe the speed with which a given gas is removed from the atmosphere. Methane has a relatively short lifetime (largely removed within a decade or so, depending on conditions), so reductions in emissions can lead to a fairly rapid decrease in concentrations as the gas is oxidized in the atmosphere.[6] Nitrous oxide has a much longer lifetime, taking more than 100 years to be substantially removed.[7] Other gases in this category include industrial gases, like those used as solvents and in air conditioning, some of which persist in the atmosphere for hundreds or thousands of years.

Carbon dioxide (CO_2) does not react chemically with other gases in the atmosphere, so it does not, strictly speaking, have a "lifetime."[8] Instead, the relationship between emissions and concentrations from year to year is determined by patterns of release (for example, through burning of fossil fuels) and uptake (for example, by vegetation and by the ocean).[9] Once CO_2 is emitted from any source, a portion of it is removed from the atmosphere over time by plant growth and absorption by the oceans, after which it continues to circulate in the land-atmosphere-ocean system until it is finally converted into stable forms in soils, deep ocean sediments, or other geological repositories (Figure 27.1).

Human Activities and the Global Carbon Dioxide Budget

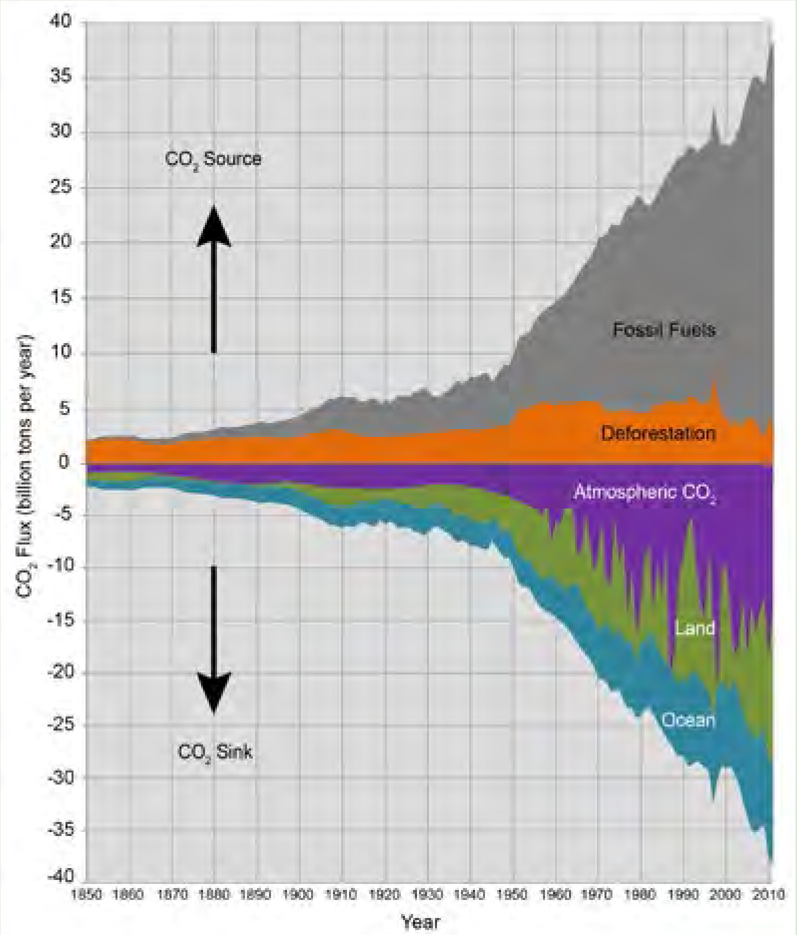

Figure 27.1. Figure shows human-induced changes in the global carbon dioxide budget roughly since the beginning of the Industrial Revolution. Emissions from fossil fuel burning are the dominant cause of the steep rise shown here from 1850 to 2012. (Global Carbon Project 2010, 2012[10]).

Of the carbon dioxide emitted from human activities in a year, about half is removed from the atmosphere by natural processes within a century, but around 20% continues to circulate and to affect atmospheric concentrations for thousands of years.[11] Stabilizing or reducing atmospheric carbon dioxide concentrations, therefore, requires very deep reductions in future emissions – ultimately approaching zero – to compensate for past emissions that are still circulating in the Earth system. Avoiding future emissions, or capturing and storing them in stable geological storage, would prevent carbon dioxide from entering the atmosphere, and would have very long-lasting effects on atmospheric concentrations.

In addition to greenhouse gases, there can be climate effects from fine particles in the atmosphere. An example is black carbon (soot), which is released from coal burning, diesel engines, cooking fires, wood stoves, wildfires, and other combustion sources. These particles have a warming influence, especially when they absorb solar energy low in the atmosphere.[12] Other particles, such as those formed from sulfur dioxide released during coal burning, have a cooling effect by reflecting some of the sun's energy back to space or by increasing the brightness of clouds (see: Ch. 2: Our Changing Climate; Appendix 3: Climate Science Supplement; and Appendix 4: FAQs).

The effect of each gas is related to both how long it lasts in the atmosphere (the longer it lasts, the greater its influence) and its potency in trapping heat. The warming influence of different gases can be compared using "global warming potentials" (GWP), which combine these two effects, usually added up over a 100-year time period. Global warming potentials are referenced to carbon dioxide – which is defined as having a GWP of 1.0 – and the combined effect of multiple gases is denoted in carbon dioxide equivalents, or CO_2-e.

The relationship between emissions and concentrations of gases can be modeled using Earth System Models.[4] Such models apply our understanding of biogeochemical processes that remove greenhouse gas from the atmosphere to predict their future concentrations. These models show that stabilizing CO_2 *emissions* would not stabilize its atmospheric concentrations but instead result in a concentration that would increase at a relatively steady rate. Stabilizing atmospheric *concentrations* of CO_2 would require reducing emissions far below present-day levels. Concentration and emissions scenarios, such as the recently developed Representative Concentration Pathways (RCPs) and scenarios developed earlier by the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES), are used in Earth System Models to study potential future climates. The RCPs span a range of atmospheric targets for use by climate modelers,[13,14] as do the SRES cases. These global analyses form a framework within which the climate contribution of U.S. mitigation efforts can be assessed. In this report, special attention is given to the SRES A2 scenario (similar to RCP 8.5), which assumes continued increases in emissions, and the SRES B1 scenario (close to RCP 4.5), which assumes a substantial reduction of emissions (Ch. 2: Our Changing Climate; Appendix 5: Scenarios and Models).

GEOENGINEERING

Geoengineering has been proposed as a third option for addressing climate change in addition to, or alongside, mitigation and adaptation. Geoengineering refers to intentional modifications of the Earth system as a means to address climate change. Three types of activities have been proposed: 1) carbon dioxide removal (CDR), which boosts CO_2 removal from the atmosphere by various means, such as fertilizing ocean processes and promoting land-use practices that help take up carbon, 2) solar radiation management (SRM), which reflects a small percentage of sunlight back into space to offset warming from greenhouse gases,[15] and 3) direct capture and storage of CO_2 from the atmosphere.[16]

Current research suggests that SRM or CDR could diminish the impacts of climate change. However, once undertaken, sudden cessation of SRM would exacerbate the climate effects on human populations and ecosystems, and some CDR might interfere with oceanic and terrestrial ecosystem processes.[17] SRM undertaken by itself would not slow increases in atmospheric CO_2 concentrations, and would therefore also fail to address ocean acidification. Furthermore, existing international institutions are not adequate to manage such global interventions. The risks associated with such purposeful perturbations to the Earth system are thus poorly understood, suggesting the need for caution and comprehensive research, including consideration of the implicit moral hazards.[18]

Section 1: U.S. Emissions and Land-Use Change

Industrial, Commercial, and Household Emissions

U.S. greenhouse gas emissions, not accounting for uptake by land use and agriculture (see Figure 27.3), rose to as high as 7,260 million tons CO_2-e in 2007, and then fell by about 9% between 2008 and 2012.[19] Several factors contributed to the decline, including the reduction in energy use in response to the 2008-2010 recession, the displacement of coal in electric generation by lower-priced natural gas, and the effect of federal and state energy and environmental policies.[20]

Carbon dioxide made up 84% of U.S. greenhouse gas emissions in 2011. Forty-one percent of these emissions were attributable to liquid fuels (petroleum), followed closely by solid fuels (principally coal in electric generation), and to a lesser extent by natural gas.[20] The two dominant production sectors responsible for these emissions are electric power generation (coal and gas) and transportation (petroleum). Flaring and cement manufacture together account for less than 1% of the total. If emissions from electric generation are allocated to their various end-uses, transportation is the largest CO_2 source, contributing a bit over one-third of the total, followed by industry at slightly over a quarter, and residential use and the commercial sector at around one-fifth each.

A useful picture of historical patterns of carbon dioxide emissions can be constructed by decomposing the cumulative change in emissions from a base year into the contributions of five driving forces: 1) decline in the CO_2 content of energy use, as with a shift from coal to natural gas in electric generation, 2) reduction in energy intensity – the energy needed to produce each unit of gross domestic product (GDP) – which results from substitution responses to energy prices, changes in the composition of the capital stock, and both autonomous and price-induced technological change, 3) changes in the structure of the economy, such as a decline in energy-intensive industries and an increase in services that use less energy, 4) growth in per capita GDP, and 5) rising population.

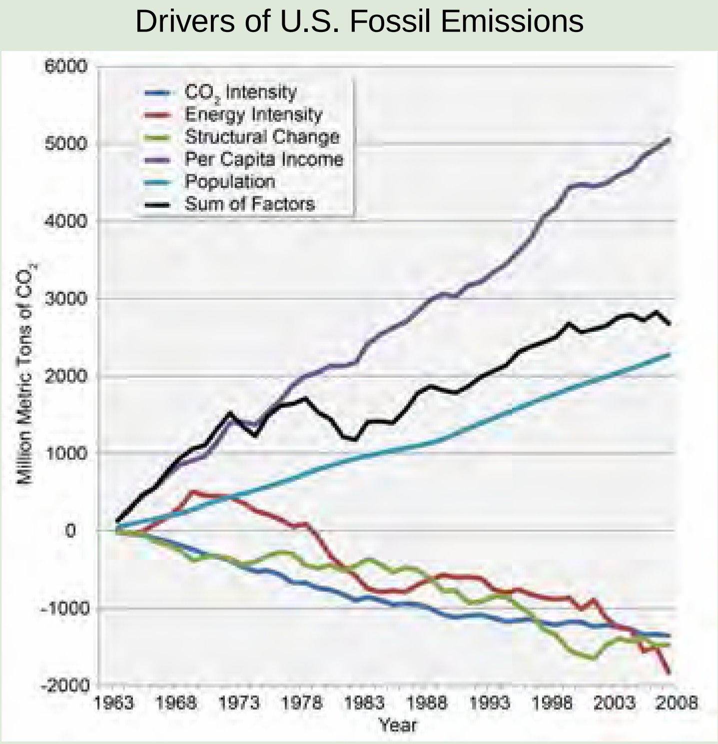

Figure 27.2. This graph depicts the changes in carbon dioxide (CO_2) emissions over time as a function of five driving forces: 1) the amount of CO_2 produced per unit of energy (CO_2 intensity); 2) the amount of energy used per unit of gross domestic product (energy intensity); 3) structural changes in the economy; 4) per capita income; and 5) population. Although CO_2 intensity and especially energy intensity have decreased significantly and the structure of the U.S. economy has changed, total CO_2 emissions have continued to rise as a result of the growth in both population and per capita income. (Baldwin and Sue Wing, 2013[21]).

Over the period 1963-2008, annual U.S. carbon dioxide emissions slightly more than doubled, because growth in emissions potential attributable to increases in population and GDP per person outweighed reductions contributed by lowered energy and carbon intensity and changes in economic structure (Figure 27.2). Each series in the figure illustrates the quantity of cumulative emissions since 1963 that would have been generated by the effect of the associated driver. By 2008, fossil fuel burning had increased CO_2 emissions by 2.7 billion tons over 1963 levels. However, by itself the observed decline in energy would have reduced emissions by 1.8 billion tons, while the observed increase in per capita GDP would have increased emissions by more than 5 billion tons.

After decades of increases, CO_2 emissions from energy use (which account for 97% of total U.S. emissions) declined by around 9% between 2008 and 2012, largely due to a shift from coal to less CO_2-intensive natural gas for electricity production.[19] Trends in driving forces shown in Figure 27.2 are expected to continue in the future, though their relative contributions are subject to significant uncertainty. The reference case projection by the U.S. Energy Information Administration (EIA) shows their net effect being a slower rate of CO_2 emissions growth than in the past, with roughly constant energy sector emissions to 2040.[22] It must be recognized, however, that emissions from energy use rise and fall from year to year, as the aforementioned driving forces vary.

The primary non-CO_2 gas emissions in 2011 were methane (9% of total CO_2-e emissions), nitrous oxide (5%), and a set of industrial gases (2%). U.S. emissions of each of these gases have been roughly constant over the past half-dozen years.[22] Emissions of methane and nitrous oxide have been roughly constant over the past couple of decades, but there has been an increase in the industrial gases as some are substituted for ozone-destroying substances controlled by the Montreal Protocol.[23]

Yet another warming influence on the climate system is black carbon (soot), which consists of fine particles that result mainly from incomplete combustion of fossil fuels and biomass. Long a public health concern, black carbon particles absorb solar radiation during their short life in the atmosphere (days to weeks). When deposited on snow and ice, these particles darken the surface and reduce the reflection of incoming solar radiation back to space. These particles also influence cloud formation in ways yet poorly quantified.[24]

Land Use, Forestry, and Agriculture

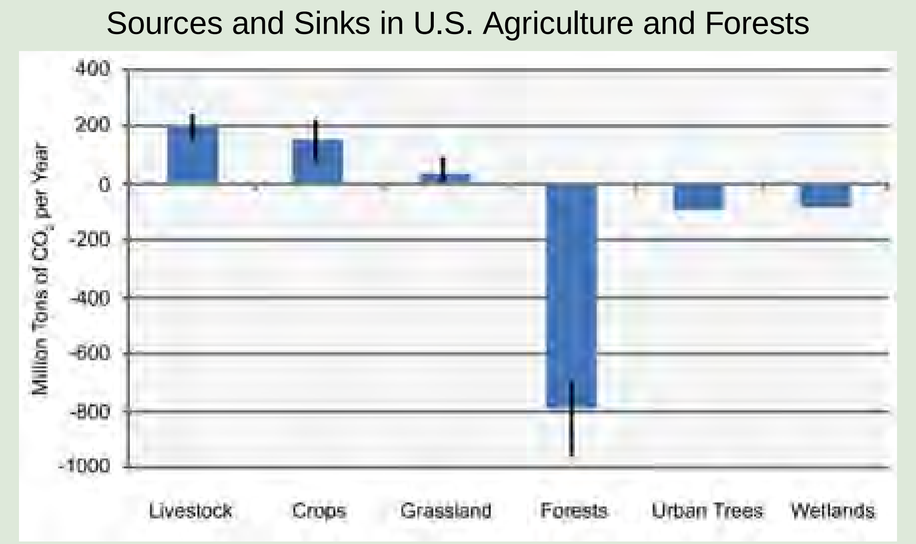

Figure 27.3 Graph shows annual average greenhouse gas emissions from land use including livestock and crop production, but does not include fossil fuels used in agricultural production. Forests are a significant "sink" that absorbs carbon dioxide from the atmosphere. All values shown are for 2008, except wetlands, which are shown for 2003. (Pacala et al. 2007;[27] USDA 2011[26]).

The main stocks of carbon in its various biological forms (plants and trees, dead wood, litter, soil, and harvested products) are estimated periodically and their rate of change, or flux, is calculated as the average annual difference between two time periods. Estimates of carbon stocks and fluxes for U.S. lands are based on land inventories augmented with data from ecosystem studies and production reports.[25,26]

U.S. lands were estimated to be a net sink of between approximately 640 and 1,074 million tons CO_2-e in the late 2000s.[26,27] Estimates vary depending on choice of datasets, models, and methodologies (see Ch. 15: Biogeochemical Cycles, "Estimating the U.S. Carbon Sink," for more discussion). This net land sink effect is the result of sources (from crop production, livestock production, and grasslands) and sinks (in forests, urban trees, and wetlands). Sources of carbon have been relatively stable over the last two decades, but sinks have been more variable. Long-term trends suggest significant emissions from forest clearing in the early 1900s followed by a sustained period of net uptake from forest regrowth over the last 70 years.[28] The amount of carbon taken up by U.S. land sinks is dominated by forests, which have annually absorbed 7% to 24% (with a best estimate of about 16%) of fossil fuel CO_2 emissions in the U.S. over the past two decades.[20]

The persistence of the land sink depends on the relative effects of several interacting factors: recovery from historical land-use change, atmospheric CO_2 and nitrogen deposition, natural disturbances, and the effects of climate variability and change – particularly drought, wildfires, and changes in the length of the growing season. Deforestation continues to cause an annual loss of 877,000 acres (137,000 square miles) of forested land, offset by a larger area gain of new forest of about 1.71 million acres (268,000 square miles) annually.[29] Since most of the new forest is on relatively low-productivity lands of the Intermountain West, and much of the deforestation occurs on high-productivity lands in the East, recent land-use changes have decreased the potential for future carbon storage.[30] The positive effects of increasing carbon dioxide concentration and nitrogen deposition on carbon storage are not likely to be as large as the negative effects of land-use change and disturbances.[31] In some regions, longer growing seasons associated with climate change may increase annual productivity.[32] Droughts and other disturbances, such as fire and insect infestations, have already turned some U.S. land regions from carbon sinks into carbon sources (see Ch. 13: Land Use & Land Cover Change and Ch. 15: Biogeochemical Cycles).[31] The current land sink may not be sustainable for more than a few more decades,[33] though there is a lack of consistency in published results about the relative effects of disturbance and other factors on net land-use emissions.[31,34]

Section 2: Activities Affecting Emissions

Early and large reductions in global emissions would be necessary to achieve the lower emissions scenarios (such as the lower B1 scenario; see Ch. 2: Our Changing Climate) analyzed in this assessment. The principal types of national actions that could effect such changes include putting a price on emissions, setting regulations and standards for activities that cause emissions, changing subsidy programs, and direct federal expenditures. Market-based approaches include cap and trade programs that establish markets for trading emissions permits, analogous to the Clean Air Act provisions for sulfur dioxide reductions. None of these price-based measures has been implemented at the national level in the United States, though cap and trade systems are in place in California and in the Northeast's Regional Greenhouse Gas Initiative. Moreover, a wide range of governmental actions are underway at federal, state, regional, and city levels using other measures, and voluntary efforts, that can reduce the U.S. contribution to total global emissions. Many, if not most of these programs are motivated by other policy objectives – energy, transportation, and air pollution – but some are directed specifically at greenhouse gas emissions, including:

- reduction in CO_2 emissions from energy end-use and infrastructure through the adoption of energy-efficient components and systems – including buildings, vehicles, manufacturing processes, appliances, and electric grid systems;

- reduction of CO_2 emissions from energy supply through the promotion of renewables (such as wind, solar, and bioenergy), nuclear energy, and coal and natural gas electric generation with carbon capture and storage; and

- reduction of emissions of non-CO_2 greenhouse gases and black carbon; for example, by lowering methane emissions from energy and waste, transitioning to climate-friendly alternatives to hydrofluorocarbons (HFCs), cutting methane and nitrous oxide emissions from agriculture, and improving combustion efficiency and means of particulate capture.

Programs underway that reduce carbon dioxide emissions include the promotion of solar, nuclear, and wind power and efficient vehicles

Federal Actions

The Federal Government has implemented a number of measures that promote energy efficiency, clean technologies, and alternative fuels.[35] A sample of these actions is provided in Table 27.1 and they include greenhouse gas regulations, other rules and regulations with climate co-benefits, various standards and subsidies, research and development, and federal procurement practices.

The U.S. Environmental Protection Agency (EPA) has a 40-year history of regulating the concentration and deposition of criteria pollutants (six common air pollutants that affect human health). A 2012 Supreme Court decision upheld the EPA's finding that greenhouse gases "endanger public health and welfare."[36] This ruling added the regulation of greenhouse gas emissions to the Agency's authority under the Clean Air Act. Actions taken and proposed under the new authority have focused on road transport and electric power generation.

The U.S. Department of Energy (DOE) provides most of the funding for a broad range of programs for energy research,

development, and demonstration. DOE also has the authority to regulate the efficiency of appliances and building codes for manufactured housing. In addition, most of the other federal agencies – including the Departments of Defense, Housing and Urban Development, Transportation, and Agriculture – have programs related to greenhouse gas mitigation.

The Administration's Climate Action Plan[37] builds on these activities with a broad range of mitigation, adaptation, and preparedness measures. The mitigation elements of the plan are in part a response to the commitment made during the 2010 Cancun Conference of the Parties of the United Nations Framework Convention on Climate Change to reduce U.S. emissions of greenhouse gases by 17% below 2005 levels by 2020. Actions proposed in the Plan include: 1) limiting carbon emissions from both new and existing power plants, 2) continuing to increase the stringency of fuel economy standards for automobiles and trucks, 3) continuing to improve energy efficiency in the buildings sector, 4) reducing the emissions of non-CO_2 greenhouse gases through a variety of measures, 5) increasing federal investments in cleaner, more efficient energy sources for both power and transportation, and 6) identifying new approaches to protect and restore our forests and other critical landscapes, in the presence of a changing climate.

City, State, and Regional Actions

Jurisdiction for greenhouse gases and energy policies is shared between the federal government and the states.[1] For example, states regulate the distribution of electricity and natural gas to consumers, while the Federal Energy Regulatory Commission regulates wholesale sales and transportation of natural gas and electricity. In addition, many states have adopted climate initiatives as well as energy policies that reduce greenhouse gas emissions. For a survey of many of these state activities, see Table 27.2. Many cities are taking similar actions.

The most ambitious state activity is California's Global Warming Solutions Act (AB 32), a law that sets a state goal to reduce greenhouse gas emissions to 1990 levels by 2020. The state program caps emissions and uses a market-based system of trading in emissions credits (cap and trade), as well as a number of regulatory actions. The most well-known, multi-state effort has been the Regional Greenhouse Gas Initiative (RGGI), formed by ten northeastern and Mid-Atlantic states (though New Jersey exited in 2011). RGGI is a cap and trade system applied to the power sector with revenue from allowance auctions directed to investments in efficiency and renewable energy.

Voluntary Actions

Corporations, individuals, and non-profit organizations have initiated a host of voluntary actions. The following examples give the flavor of the range of efforts:

- The Carbon Disclosure Project has the largest global collection of self-reported climate change and water-use information. The system enables companies to measure, disclose, manage, and share climate change and water-use information. Some 650 U.S. signatories include banks, pension funds, asset managers, insurance companies, and foundations.

- Many local governments are undertaking initiatives to reduce greenhouse gas emissions within and outside of their organizational boundaries.[38] For example, over 1,055 municipalities from all 50 states have signed the U.S. Mayors Climate Protection Agreement,[39] and many of these communities are actively implementing strategies to reduce their greenhouse gas footprint.

- Under the American College and University Presidents' Climate Commitment (ACUPCC), 679 institutions have pledged to develop plans to achieve net-neutral climate emissions through a combination of on-campus changes and purchases of emissions reductions elsewhere.

- Voluntary compliance with efficiency standards developed by industry and professional associations, such as the building codes of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), is widespread.

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- Federal voluntary programs include Energy STAR, a labeling program that identifies energy efficient products for use in residential homes and commercial buildings and plants, and programs and partnerships devoted to reducing methane emissions from fossil fuel production and landfill sources and high GWP emissions from industrial activities and agricultural conservation programs.

Costs of Emissions Reductions

The national cost of achieving U.S. emissions reductions over time depends on the level of reduction sought and the particular measures employed. Studies of price-based policies, such as a cap and trade system, indicate that a 50% reduction in emissions by 2050 could be achieved at a cost of a year or two of projected growth in gross domestic product over the period (for example, Paltsev et al. 2009; EIA 2009[40]). However, because of differences in analysis method, and in assumptions about economic growth and technology change, cost projections vary considerably even for a policy applying price penalties.[41] Comparisons of emissions reduction by prices versus regulations show that a regulatory approach can cost substantially more than a price-based policy.[42]

CO-BENEFITS FOR AIR POLLUTION AND HUMAN HEALTH

Actions to reduce greenhouse gas emissions can yield co-benefits for objectives apart from climate change, such as energy security, health, ecosystem services, and biodiversity.[43,44] The co-benefits for reductions in air pollution have received particular attention. Because air pollutants and greenhouse gases share common sources, particularly from fossil fuel combustion, actions to reduce greenhouse gas emissions also reduce air pollutants. While some greenhouse gas reduction measures might increase other emissions, broad programs to reduce greenhouse gases across an economy or a sector can reduce air pollutants markedly.[14,45] (Unfortunately for climate mitigation, cutting sulfur dioxide pollution from coal burning also reduces the cooling influence of reflective particles formed from these emissions in the atmosphere.[46])


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There is significant interest in quantifying the air pollution and human health co-benefits of greenhouse gas mitigation, particularly from the public health community,[44,47] as the human health benefits can be immediate and local, in contrast to the long-term and widespread effects of climate change.[48] Many studies have found that monetized health and pollution control benefits can be of similar magnitude to abatement costs (for example, Nemet et al. 2010; Burtraw et al. 2003[48,49]). Methane reductions have also been shown to generate health benefits from reduced ozone.[50] Similarly, in developing nations, reducing black carbon from household cook stoves substantially reduces air pollution-related illness and death.[51] Ancillary health benefits in developing countries typically exceed those in developed countries for a variety of reasons.[48] But only in very few cases are these ancillary benefits considered in analyses of climate mitigation policies.

Section 3: Preparation for Potential Future Mitigation Action

To meet the emissions reduction in the lower (B1) scenario used in this assessment (Ch. 2: Our Changing Climate) under reasonable assumptions about managing costs, annual global CO_2 emissions would need to peak at around 44 billion tons within the next 25 years or so and decline steadily for the rest of the century. At the current rate of emissions growth, the world is on a path to exceed the 44 billion ton level within a decade (see "Emissions Scenarios and RCPs"). Thus achievement of a global emissions path consistent with the B1 scenario will require strenuous action by all major emitters.

Policies already enacted and other factors lowered U.S. emissions in recent years. The Annual Energy Outlook prepared by the EIA, which previously forecasted sustained growth in emissions, projected in 2013 that energy-related U.S. CO_2 emissions would remain roughly constant for the next 25 years.[22]

Moreover, through the President's Climate Action Plan, the Administration has committed to additional measures not yet reflected in the EIA's projections, with the goal of reducing emissions about 17% below 2005 levels by 2020. Still, additional and stronger U.S. action, as well as strong action by other major emitters, will be needed to meet the long-term global emission reductions reflected in the B1 scenario.

Achieving the B1 emissions path would require substantial decarbonization of the global economy by the end of this century, implying a fundamental transformation of the global energy system. Details of the energy mix along the way differ among analyses, but the implied involvement by the U.S. can be seen in studies carried out under the U.S. Climate Change Science Program[54] and the Energy Modeling Forum.[55,56] In these studies, direct burning of coal without carbon capture is essentially excluded from the power system, and the same holds for natural gas toward the end of the century – to be replaced by some combination of coal or gas with carbon capture and storage, nuclear generation, and renewables. Biofuels and electricity are projected to substitute for oil in the transport sector. A substantial component of the task is accomplished with demand reduction, through efficiency improvement, conservation, and shifting to an economy less dependent on energy services.

The challenge is great enough even starting today, but delay by any of the major emitters makes meeting any such target even more difficult and may rule out some of the more ambitious goals.[54,55] A study of the climate change threat and potential responses by the U.S. National Academies therefore concludes that there is "an urgent need for U.S. action to reduce greenhouse emissions."[57] The National Research Council (NRC) goes on to suggest alternative national-level strategies that might be followed, including an economy-wide system of prices on greenhouse gas emissions and a portfolio of possible regulatory measures and subsidies. Deciding these matters will be a continuing task, and U.S. Administrations and Congress face a long series of choices about whether to take additional mitigation actions and how best to do it. Two supporting activities will help guide this process: opening future technological options and development of ever-more-useful assessments of the cost effectiveness and benefits of policy choices.

EMISSIONS SCENARIOS AND RCPs

The Representative Concentration Pathways (RCPs) specify alternative limits to human influence on the Earth's energy balance, stated in watts per square meter (W/m^2) of the Earth's surface.[13,52] The A2 emissions scenario implies atmospheric concentrations with radiative forcing slightly lower than the highest RCP, which is 8.5 W/m^2. The lower limits, at 6.0, 4.5 and 2.6 W/m^2, imply ever-greater mitigation efforts. The B1 scenario (rapid emissions reduction) is close to the 4.5 W/m^2 RCP[53] and to a similar case (Level 2) analyzed in a previous federal study.[54] Those assessments find that, to limit the economic costs, annual global CO_2 emissions from fossil fuels and industrial sources like cement manufacture, need to peak by 2035 to 2040 at around 44 billion tons of CO_2, and decline thereafter. The scale of the task can be seen in the fact that these global emissions were already at 34 billion tons CO_2 in 2011, and over the previous decade they rose at around 0.92 billion tons of CO_2 per year.[10] The lowest RCP would require an even more rapid turnaround and negative net emissions – that is, removing more CO_2 from the air than is emitted globally – in this century.[52]

Many technologies are potentially available to accomplish emissions reduction. They include ways to increase the efficiency of fossil energy use and facilitate a shift to low-carbon energy sources, sources of improvement in the cost and performance of renewables (for example, wind, solar, and bioenergy) and nuclear energy, ways to reduce the cost of carbon capture and storage, means to expand terrestrial sinks through management of forests and soils and increased agricultural productivity,[2] and phasing down HFCs. In addition to the research and development carried out by private sector firms with their own funds, the Federal Government traditionally supports major programs to advance these technologies. This support is accomplished in part by credits and deductions in the tax code, and in part by federal expenditure. For example, the 2012 federal budget devoted approximately $6 billion to clean energy technologies.[58] Success in these ventures, lowering the cost of greenhouse gas reduction, can make a crucial contribution to future policy choices.[1]

Because they are in various stages of market maturity, the costs and effectiveness of many of these technologies remain uncertain: continuing study of their performance is important to understanding their role in future mitigation decisions.[59] In addition, evaluation of broad policies and particular mitigation measures requires frameworks that combine information from a range of disciplines. Study of mitigation in the near future can be done with energy-economic models that do not assume large changes in the mix of technologies or changes in the structure of the economy. Analysis over the time spans relevant to stabilization of greenhouse gas concentrations, however, requires Integrated Assessment Models, which consider all emissions drivers and policy measures that affect them, and that take account of how they are related to the larger economy and features of the climate system.[54,55,60] This type of analysis is also useful for exploring the relations between mitigation and measures to adapt to a changing climate.

Continued development of these analytical capabilities can help support decisions about national mitigation and the U.S. position in international negotiations. In addition, as shown above, mitigation is being undertaken by individuals and firms as well as by city, state, and regional governments. The capacity for mitigation from individual and household behavioral changes, such as increasing energy end-use efficiency with available technology, is known to be large.[63] Although there is capacity, there is not always broad acceptance of those behavioral changes, nor is there sufficient understanding of how to design programs to encourage such changes.[64] Behavioral and institutional research on how such choices are made and the results evaluated would be extremely beneficial. For many of these efforts, understanding of cost and effectiveness is limited, as is understanding of aspects of public support and institutional performance; so additional support for studies of these activities is needed to ensure that resources are efficiently employed.

INTERACTIONS BETWEEN ADAPTATION AND MITIGATION

There are various ways in which mitigation efforts and adaptation measures are interdependent (see Ch. 28: Adaptation). For example, the use of plant material as a substitute for petroleum-based transportation fuels or directly as a substitute for burning coal or gas for electricity generation has received substantial attention.[61] But land used for mitigation purposes is potentially not available for food production, even as the global demand for agricultural products continues to rise.[62] Conversely, land required for adaptation strategies, like setting aside wildlife corridors or expanding the extent of conservation areas, is potentially not available for mitigation involving the use of plant material, or active management practices to enhance carbon storage in vegetation or soils. These possible interactions are poorly understood but potentially important, especially as climate change itself affects vegetation and ecosystem productivity and carbon storage. Increasing agricultural productivity to adapt to climate change can also serve to mitigate climate change.

Section 4: Research Needs

- Engineering and scientific research is needed on the development of cost-effective energy use technologies (devices, systems, and control strategies) and energy supply technologies that produce little or no CO_2 or other greenhouse gases.

- Better understanding of the relationship between emissions and atmospheric greenhouse gas concentrations is needed to more accurately predict how the atmosphere and climate system will respond to mitigation measures.

- The processes controlling the land sink of carbon in the U.S. require additional research, including better monitoring and analysis of economic decision-making about the fate of land and how it is managed, as well as the inherent ecological processes and how they respond to the climate system.

- Uncertainties in model-based projections of greenhouse gas emissions and of the effectiveness and costs of policy measures need to be better quantified. Exploration is needed of the effects of different model structures, assumptions about model parameter values, and uncertainties in input data.

- Social and behavioral science research is needed to inform the design of mitigation measures for maximum participation and to prepare a consistent framework for assessing cost effectiveness and benefits of both voluntary mitigation efforts and regulatory and subsidy programs.

Table 27.1. A number of existing federal laws and regulations target ways to reduce future climate change by decreasing greenhouse gas emissions emitted by human activities.

Sample Federal Mitigation Measures
Greenhouse Gas Regulations
Emissions Standards for Vehicles and Engines -- For light-duty vehicles, rules establishing standards for 2012-2016 model years and 2017-2025 model years. -- For heavy- and medium-duty trucks, a rule establishing standards for 2014-2018 model years.
Carbon Pollution Standard for New Power Plants -- A proposed rule setting limits on CO_2 emissions from future power plants.
Stationary Source Permitting -- A rule setting greenhouse gas emissions thresholds to define when permits under the New Source Review Prevention of Significant Deterioration and Title V Operating Permit programs are required for new and modified industrial facilities.
Greenhouse Gas Reporting Program -- A program requiring annual reporting of greenhouse gas data from large emission sources and suppliers of products that emit greenhouse gases when released or combusted.
Other Rules and Regulations with Climate Co-Benefits
Oil and Natural Gas Air Pollution Standards -- A rule revising New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants for certain components of the oil and natural gas industry.
Mobile Source Control Programs -- Particle control regulations affecting mobile sources (especially diesel engines) that reduce black carbon by controlling direct particle emissions. -- The requirement to blend increasing volumes of renewable fuels.
National Forest Planning -- Identification and evaluation of information relevant to a baseline assessment of carbon stocks. -- Reporting of net carbon stock changes on forestland.
Standards and Subsidies
Appliance and Building Efficiency Standards -- Energy efficiency standards and test procedures for residential, commercial, industrial, lighting, and plumbing products. -- Model residential and commercial building energy codes, and technical assistance to state and local governments, and non-governmental organizations.
Financial Incentives for Efficiency and Alternative Fuels and Technology -- Weatherization assistance for low-income households, tax incentives for commercial and residential buildings and efficient appliances, and support for state and local efficiency programs. -- Tax credits for biodiesel and advanced biofuel production, alternative fuel infrastructure, and purchase of electric vehicles. -- Loan guarantees for innovative energy or advanced technology vehicle production and manufacturing; investment and production tax credits for renewable energy.
Funding of Research, Development, Demonstration, and Deployment
-- Programs on clean fuels, energy end-use and infrastructure, CO_2 capture and storage, and agricultural practices.
Federal Agency Practices and Procurement
-- Executive orders and federal statutes requiring federal agencies to reduce building energy and resource consumption intensity and to procure alternative fuel vehicles. -- Agency-initiated programs in most departments oriented to lowering energy use and greenhouse gas emissions.

Table 27.2. Most states and Native communities have implemented programs to reduce greenhouse gases or adopt increased energy efficiency goals.

State Climate and Energy Initiatives
Examples of greenhouse gas policies include:
Greenhouse Gas Reporting and Registries http://www.c2es.org/us-states-regions/policy-maps/ghg-reporting[65]
Greenhouse Gas Emissions Targets http://www.c2es.org/us-states-regions/policy-maps/emissions-targets[66]
CO_2 Controls on Electric Power plants http://www.edf.org/sites/default/files/state-ghg-standards-03132012.pdf[67]
Low-Carbon Fuel Standards http://www.c2es.org/us-states-regions/policy-maps/low-carbon-fuel-standard[68]
Climate Action Plans http://www.c2es.org/us-states-regions/policy-maps/action-plan[69]
Cap and Trade Programs http://arb.ca.gov/cc/capandtrade/capandtrade.htm[70]
Regional Agreements http://www.c2es.org/us-states-regions/regional-climate-initiatives#WCI[71]
Tribal Communities http://www.epa.gov/statelocalclimate/tribal[72]
States have also taken a number of energy measures, motivated in part by greenhouse gas concerns. For example: Renewable Portfolio Standards http://www.dsireusa.org/documents/summarymaps/RPS_map.pdf[73]
Energy Efficiency Resource Standards http://www.dsireusa.org/documents/summarymaps/EERS_map.pdf[74]
Property Tax Incentives for Renewables http://www.dsireusa.org/documents/summarymaps/[75]

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:
Evaluation of literature by Coordinating Lead Authors

KEY MESSAGE #1 TRACEABLE ACCOUNT

Carbon dioxide is removed from the atmosphere by natural processes at a rate that is roughly half of the current rate of emissions from human activities. Therefore, mitigation efforts that only stabilize global emissions will not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase. The same is true for other long-lived greenhouse gases.

Description of evidence base

The message is a restatement of conclusions derived from the peer-reviewed literature over nearly the past 20 years (see Section 1 of chapter). Publications have documented the long lifetime of CO_2 in the atmosphere, resulting in long time lags between action and reduction,[9,11,76] and Earth System Models have shown that stabilizing emissions will not immediately stabilize atmospheric concentrations, which will continue to increase.[4]

New information and remaining uncertainties

There are several important uncertainties in the current carbon cycle, especially the overall size, location, and dynamics of the land-use sink[9,11] and technological development and performance.

Simulating future atmospheric concentrations of greenhouse gases requires both assumptions about economic activity, stringency of any greenhouse gas emissions control, and availability of technologies, as well as a number of assumptions about how the changing climate system affects both natural and anthropogenic sources.

Assessment of confidence based on evidence

Very High. Observations of changes in the concentrations of greenhouse gases are consistent with our understanding of the broad relationships between emissions and concentrations.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

To meet the lower emissions scenario (B1) used in this assessment, global mitigation actions would need to limit global carbon dioxide emissions to a peak of around 44 billion tons per year within the next 25 years and decline thereafter. In 2011, global emissions were around 34 billion tons, and have been rising by about 0.9 billion tons per year for the past decade. Therefore, the world is on a path to exceed 44 billion tons per year within a decade.

Description of evidence base

A large number of emissions scenarios have been modeled, with a number of publications showing what would be required to limit CO_2[13,53,54,77] to any predetermined limit. At current concentrations and rate of rise, the emissions of CO_2 would need to peak around

44 billion tons within the next 25 years in order to stabilize concentrations as in the B1 scenario. Given the rate of increase in recent years,[10] this limit is expected to be surpassed.[78]

New information and remaining uncertainties

Uncertainties about the carbon cycle could affect these calculations, but the largest uncertainties are the assumptions made about the strength and cost of greenhouse gas emissions policies.

Assessment of confidence based on evidence

The confidence in the conclusion is **high**. This is a contingent conclusion, though – we do not have high confidence that the current emission rate will be sustained. However, we do have high confidence that if we do choose to limit concentrations as in the B1 scenario, emissions will need to peak soon and then decline.

Key message #3 Traceable Account

Over recent decades, the U.S. economy has emitted a decreasing amount of carbon dioxide per dollar of gross domestic product. Between 2008 and 2012, there was also a decline in the total amount of carbon dioxide emitted annually from energy use in the United States as a result of a variety of factors, including changes in the economy, the development of new energy production technologies, and various government policies.

Description of evidence base

Trends in greenhouse gas emissions intensity are analyzed and published by governmental reporting agencies.[20,23,26] Published, peer-reviewed literature cited in Section 2 of the Mitigation Chapter supports the conclusions about why these trends have occurred.[79]

New information and remaining uncertainties

Economic and technological forecasts are highly uncertain.

Assessment of confidence based on evidence

High. The statement is a summary restatement of published analyses by government agencies and interpretation from the reviewed literature.

Key message #4 Traceable Account

Carbon storage in land ecosystems, especially forests, has offset around 17% of annual U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" may not be sustainable.

Description of evidence base

Underlying data come primarily from U.S. Forest Service Forest Inventory and Analysis (FIA) plots, supplemented by additional ecological data collection efforts. Modeling conclusions come from peer-reviewed literature. All references are in Section 2 of the Mitigation Chapter. Studies have shown that there is a large land-use carbon sink in the United States.[26,27,28] Many publications attribute this sink to forest re-growth, and the sink is projected to decline as a result of forest aging[30,31,33] and factors like drought, fire, and insect infestations[31] reducing the carbon sink of these regions.

New information and remaining uncertainties

FIA plots are measured extremely carefully over long time periods, but do not cover all U.S. forested land. Other U.S. land types must have carbon content estimated from other sources. Modeling relationships between growth and carbon content, and taking CO_2 and climate change into account have large scientific uncertainties associated with them.

Assessment of confidence based on evidence

High. Evidence of past trends is based primarily on government data sources, but these also have to be augmented by other data and models in order to incorporate additional land-use types. Projecting future carbon content is consistent with published models, but these have intrinsic uncertainties associated with them.

Key message #5 Traceable Account

Both voluntary activities and a variety of policies and measures that lower emissions are currently in place at federal, state, and local levels in the United States, even though there is no comprehensive national climate legislation. Over the remainder of this century, aggressive and sustained greenhouse gas emission reductions by the United States and by other nations would be needed to reduce global emissions to a level consistent with the lower scenario (B1) analyzed in this assessment.

Description of evidence base

The identification of state, local, regional, federal, and voluntary programs that will have an effect of reducing greenhouse gas emissions is a straightforward accounting of both legislative action and announcements of the implementation of such programs. Some of the programs include the Carbon Disclosure Project (CDP), the American College and University Presidents' Climate Commitment (ACUPCC), U.S. Mayors Climate Protection Agreement,[39] and many other local government initiatives.[38] Several states have also adapted climate policies including California's Global Warming Solutions Act (AB 32) and the Regional Greenhouse Gas Initiative (RGGI). The assertion that they will not lead to a reduction of US CO_2 emissions is supported by calculations from the U.S. Energy Information Administration.

New information and remaining uncertainties

The major uncertainty in the calculation about future emissions levels is whether a comprehensive national policy will be implemented.

Assessment of confidence based on evidence

Very High. There is recognition that the implementation of voluntary programs may differ from how they are originally planned, and that institutions can always choose to leave voluntary programs (as is happening with RGGI, noted in the chapter). The statement about the future of U.S. CO_2 emissions cannot be taken as a prediction of what will happen – it is a conditional statement based on an assumption of no comprehensive national legislation or regulation.

Climate Change Impacts in the United States

CHAPTER 28
ADAPTATION

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On the Web http://nca2014.globalchange.gov/report/response-strategies/adaptation

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

28 ADAPTATION

KEY MESSAGES

1. **Substantial adaptation planning is occurring in the public and private sectors and at all levels of government; however, few measures have been implemented and those that have appear to be incremental changes.**
2. **Barriers to implementation of adaptation include limited funding, policy and legal impediments, and difficulty in anticipating climate-related changes at local scales.**
3. **There is no "one-size fits all" adaptation, but there are similarities in approaches across regions and sectors. Sharing best practices, learning by doing, and iterative and collaborative processes including stakeholder involvement, can help support progress.**
4. **Climate change adaptation actions often fulfill other societal goals, such as sustainable development, disaster risk reduction, or improvements in quality of life, and can therefore be incorporated into existing decision-making processes.**
5. **Vulnerability to climate change is exacerbated by other stresses such as pollution, habitat fragmentation, and poverty. Adaptation to multiple stresses requires assessment of the composite threats as well as tradeoffs among costs, benefits, and risks of available options.**
6. **The effectiveness of climate change adaptation has seldom been evaluated, because actions have only recently been initiated and comprehensive evaluation metrics do not yet exist.**

Over the past few years, the focus moved from the question "Is climate changing?" to the equally important question: "Can society manage unavoidable changes and avoid unmanageable changes?"[1,2] Research demonstrates that both mitigation (efforts to reduce future climate changes) and adaptation (efforts to reduce the vulnerability of society to climate change impacts) are needed in order to minimize the damages from human-caused climate change and to adapt to the pace and ultimate magnitude of changes that will occur.[3,4,5]

Adaptation and mitigation are closely linked; adaptation efforts will be more difficult, more costly, and less likely to succeed if significant mitigation actions are not taken.[2,6] The study and application of adaptation in the climate change realm is nascent compared to the many analyses of mitigation policies and practices to reduce emissions. Uncertainties about future socioeconomic conditions as well as future climate changes can make it difficult to arrive at adaptation decisions now. However, the pace and magnitude of projected change emphasize the need to be prepared for a wide range and intensity of climate impacts in the future. Planning and managing based on the climate of the last century means that tolerances of some infrastructure and species will be exceeded.[5,7,8] For example, building codes and landscaping ordinances will likely need to be updated not only for energy efficiency but also to conserve water supplies, protect against disease vectors, reduce susceptibility to heat stress, and improve protection against extreme events.[5,9] Although there is uncertainty about future conditions, research indicates that intelligent adaptive actions can still be taken now.[10,11] Climate change projections have inherent uncertainties, but it is still important to develop, refine, and deploy tools and approaches that enable iterative decision-making and increase flexibility and robustness of climate change responses (Ch. 2: Our Changing Climate).[12]

Climate change affects human health, natural ecosystems, built environments, and existing social, institutional, and legal arrangements. Adaptation considerations include local, state, regional, national, and international issues. For example, the implications of international arrangements need to be considered in the context of managing the Great Lakes, the Columbia River, and the Colorado River to deal with drought.[13,14] Both "bottom up" community planning and "top down" national strategies[11] may help regions deal with impacts such as increases in electrical brownouts, heat stress, floods, and wildfires. Such a mix of approaches will require cross-boundary coordination at multiple levels as operational agencies integrate adaptation planning into their programs.

Adaptation actions can be implemented reactively, after changes in climate occur, or proactively, to prepare for projected changes.[11] Proactively preparing can reduce the harm from certain climate change impacts, such as increasingly intense extreme events, shifting zones for agricultural crops, and rising sea levels, while also facilitating a more rapid and efficient response to changes as they happen. This chapter highlights efforts at the federal, regional, state, tribal, and local levels, as well as initiatives in the corporate and non-governmental sectors to build adaptive capacity and resilience in response to climate change. While societal adaptation to *climate variability* is as old as civilization itself,[15] the focus of this chapter is on preparing for unprecedented human-induced *climate change* through adaptation. A map of illustrative adaptation activities and four detailed case examples that highlight ongoing adaptation activity across the U.S. are provided in Section 4 of this chapter.

ADAPTATION KEY TERMS DEFINITIONS*

Adapt, Adaptation: Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.

Adaptive Capacity: The potential of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, take advantage of opportunities, and cope with the consequences.

Mitigation: Technological change and substitutions that reduce resource inputs and emissions per unit of output. Although several social, economic, and technological actions would reduce emissions, with respect to climate change, mitigation means implementing actions to reduce greenhouse gas emissions or increase the amount of carbon dioxide absorbed and stored by natural and man-made carbon sinks (see Ch. 27: Mitigation).

Multiple Stressors: Stress that originates from different sources that affect natural, managed, and socioeconomic systems and can cause impacts that are compounded and sometimes unexpected. An example would be when economic or market stress combines with drought to negatively impact farmers.

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

Risk: A combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

*Definitions adapted from (IPCC 2007; [16] NRC 2007,[17] 2010[11]).

Adaptation Activities in the United States

Federal Government

Federal leadership, guidance, information, and support are vital to planning for and implementing adaptation actions at all scales and in all affected sectors of society (Table 28.1).[11,18,19,20] Several new federal climate adaptation initiatives and strategies have been developed in recent years, including:

- Executive Order (EO) 13514, requiring federal agencies to develop recommendations for strengthening policies and programs to adapt to the impacts of climate change;[21]

- the release of President Obama's Climate Action Plan in June 2013, which has as one of its three major pillars, preparing the United States for the impacts of climate change, including building stronger and safer communities and infrastructure, protecting the economy and natural resources, and using sound science to manage climate impacts;[22]

- the creation of an Interagency Climate Change Adaptation Task Force (ICCATF) (now the Council on Climate Preparedness and Resilience, per Executive Order 13653[23]) that led to the development of national principles for adaptation and is leading to crosscutting and government-wide adaptation policies;

- the development of three crosscutting national adaptation strategies focused on integrating federal, and often state, local, and tribal efforts on adaptation in key sectors: 1) the National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate;[24] 2) the National Fish, Wildlife and Plants Climate Adaptation Strategy;[25] and 3) a priority objective on resilience and adaptation in the National Ocean Policy Implementation Plan;[26]

- a new decadal National Global Change Research Plan (2012–2021) that includes elements related to climate adaptation, such as improving basic science, informing decisions, improving assessments, and communicating with and educating the public;[27]

- the development of several interagency and agency-specific groups focused on adaptation, including a "community of practice" for federal agencies that are developing and implementing adaptation plans, an Adaptation Science Workgroup inside the U.S. Global Change Research Program (USGCRP), and several agency specific climate change and adaptation task forces; and

- a November 2013 Executive Order entitled "Preparing the United States for the Impacts of Climate Change" that, among other things, calls for the modernizing of federal programs to support climate resilient investments, managing lands and waters for climate preparedness and resilience, the creation of a Council on Climate Preparedness and Resilience, and the creation of a State, Local, and Tribal Leaders Task Force on Climate Preparedness and Resilience.[23]

Federal agencies are all required to plan for adaptation. Actions include coordinated efforts at the White House, regional and cross-sector efforts, agency-specific adaptation plans, as well as support for local-level adaptation planning and action. Table 28.1 lists examples, but is not intended as a comprehensive list.

Table 28.1. Examples of Individual Federal Agency Actions to Promote, Implement, and Support Adaptation at Multiple Scales*

Agency	Component	Action	Description
All Federal Agencies		Developed Adaptation Plans as part of their annual Strategic Sustainability Performance Plans	The 2012 Strategic Sustainability Performance Plans for Federal agencies contain specific sections on adaptation. Agencies are required to evaluate climate risks and vulnerabilities to manage both short- and long-term effects on missions and operations.
Department of Health and Human Services (HHS)	Centers for Disease Control and Prevention (CDC)	Climate-Ready States and Cities Initiative	Through their first climate change cooperative agreements in 2010, CDC awarded $5.25 million to ten state and local health departments to assess risks and develop programs to address climate change related challenges.
Department of Agriculture (USDA)		Integrating climate change objectives into plans and networks	USDA is using existing networks such as the Cooperative Extension Service, the Natural Resource Conservation Districts, and the Forest Service's Climate Change Resource Center to provide climate services to rural and agricultural stakeholders.
USDA	Forest Service	Developed a *National Roadmap for Responding to Climate Change* and a *Guidebook for Developing Adaptation Options*, among many resources	The *National Roadmap* was developed in 2010 to identify short- and long-term actions to reduce climate change risks to the nation's forests and grasslands. The *Guidebook* builds on this previous work and provides science-based strategic and tactical approaches to adaptation.
Department of Commerce (DOC)	NOAA	Supporting research teams and local communities on adaptation-related issues and develops tools and resources	Through the Regional Integrated Sciences and Assessments (RISAs) program, develop collaboration between researchers and managers to better manage climate risks. Through the Regional Climate Centers (RCCs) and the Digital Coast partnership, deliver science to support decision-making.
Department of Defense (DoD)		Developed a DoD Climate Change Adaptation Roadmap	DoD released its initial Department-level Climate Change Adaptation Roadmap in 2012. The Roadmap identifies four goals that serve as the foundation for guiding the Department's response to climate change that include using a robust decision making approach based on the best available science.

Table 28.1. Examples of Individual Federal Agency Actions to Promote, Implement, and Support Adaptation at Multiple Scales* (Continued)

DoD	U.S. Army Corps of Engineers (USACE), Civil Works Program	Developed climate change adaptation plan; making progress in priority areas including vulnerability assessments and development of policy and guidance	The USACE Civil Works Program initial climate change adaptation plan in 2011 has a goal to reduce vulnerabilities and improve resilience of water resources infrastructure impacted by climate change. Vulnerability assessments and pilot projects are in progress. Other guidance is underway.
DoD	Department of the Navy	Developed road maps for adaptation in the Arctic and across the globe	The Navy Arctic Roadmap (November 2009) promotes maritime security and naval readiness in a changing Arctic. The Climate Change Roadmap (May 2010) examines broader issues of climate change impacts on Navy missions and capabilities globally.
Department of Energy (DOE)		Develop higher spatial and temporal scales of climate projections and integrate adaptation and climate considerations into integrated assessments	Develops community-based, high-resolution (temporal and spatial) models for climate projections and integrated assessment models that increasingly reflect multi-sectoral processes and interactions, multiple stressors, coupled impacts, and adaptation potential.
DOE		Developed climate change adaptation plan, and completed comprehensive study of vulnerabilities to the energy sector of climate change and extreme weather	The 2013 DOE Report "U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather" examines current and potential future impacts of climate trends and identifies activities underway and potential opportunities to enhance energy system climate preparedness and resilience.
Department of Homeland Security (DHS)	Federal Emergency Management Agency (FEMA)	Works with communities across the Nation to help them prioritize their activities to reduce risks	FEMA released a Climate Change Adaptation Policy Statement establishing the Agency's approach to supporting the Department in ensuring resilience to disasters in the face of climate change. FEMA's action areas focus on developing actionable "future risk" tools, enabling state and local adaptation, and building resilience capabilities.
Department of the Interior (DOI)	Fish and Wildlife Service (FWS)	Developed a FWS climate change strategic plan (2010) and established a network of Landscape Conservation Cooperatives (LCCs)	Established a framework to help ensure the sustainability of fish, wildlife, plants, and habitats in the face of climate change. Created a network of 22 LCCs to promote shared conservation goals, approaches, and resource management planning and implementation across the United States.
DOI	U.S. Geological Survey (USGS)	Established a network of Climate Science Centers (CSCs)	DOI operates a National Climate Change and Wildlife Center and eight regional CSCs, which provide scientific information and tools that land, water, wildlife, and cultural resource managers and other stakeholders can apply to anticipate, monitor, and adapt to climate change.
DOI	National Park Service (NPS)	Climate Change Response Strategy (2010), Climate Change Action Plan (2012), and Green Parks Plan (2012)	NPS actions span climate change science, adaptation, mitigation, and communication across national parks, including exhibits for park visitors, providing climate trend information for all national parks, risk screening and adaptation for coastal park units, and implementing scenario planning tools.
DOI	Bureau of Land Management (BLM)	Rapid Ecoregional Assessments (REAs)	REAs synthesize information about resource conditions and trends within an ecoregion; assess impacts of climate change and other stressors; map areas best-suited for future development; and establish baseline environmental conditions, against which to gauge management effectiveness.

Table 28.1. Examples of Individual Federal Agency Actions to Promote, Implement, and Support Adaptation at Multiple Scales* (Continued)

Department of Transportation (DOT)	Federal Highway Administration (FHWA)	Developed Risk Assessment Model for transportation decisions	DOT worked with five local and state transportation authorities to develop a conceptual Risk Assessment Model to identify which assets are: a) most exposed to climate change threats and/or b) associated with the most serious potential consequences of climate change threats. Completed November 2011.
DOT		Comprehensive study of climate risks to Gulf Coast transportation infrastructure followed by in-depth study of Mobile, AL	Phase 1 of the 2008 study assessed transportation infrastructure vulnerability to climate change impacts across the Gulf. Phase 2, to be completed in 2013, focuses on Mobile, AL. This effort will develop transferable tools for transportation planners.
Environmental Protection Agency (EPA)		Established the Climate Ready Estuaries program, the Climate Ready Water Utilities initiative, and a tribal climate change adaptation planning training program	These selected EPA initiatives provide resources and tools to build the capacity of coastal managers, water utilities, and tribal environmental professionals to plan for and implement adaptation strategies.
National Aeronautics and Space Administration (NASA)		Initiated NASA's Climate Adaptation Science Investigator (CASI) Workgroup to partner NASA scientists, engineers, and institutional stewards	The CASI team builds capacity to address climate change at NASA facilities by downscaling facility-specific climate hazard information and projections; conducting customized climate research for each location; and leading resilience and adaptation workshops that spur community-based responses.

*Material provided in table is derived directly from Agency representatives and Agency websites. These are select examples and should not be considered all-inclusive.

Federal agencies can be particularly helpful in facilitating climate adaptation by:

- fostering the stewardship of public resources and maintenance of federal facilities, services, and operations such as defense, emergency management, transportation, and ecosystem conservation in the face of a changing climate;[11,28,29,30]
- providing usable information and financial support for adaptation;[11,20,30]
- facilitating the dissemination of best practices and supporting a clearinghouse to share data, resources, and lessons learned;[11,20,31]
- dealing with and anticipating impacts that cross geopolitical boundaries, assisting in disaster response, and supporting flexible regulatory frameworks;[11,30]
- ensuring the establishment of federal policies that allow for "flexible" adaptation efforts and take steps to avoid unintended consequences;[30,32] and
- building public awareness.[33]

States

States have become important actors in national climate change related efforts. State governments can create policies and programs that encourage or discourage adaptation at other governance scales (such as counties or regions)[34] through regulation and by serving as laboratories for innovation.[35,36] Although many of these actions are not specifically designed to address climate change, they often include climate adaptation components.

Many state-level climate change-specific adaptation actions focus on planning. As of 2013, fifteen states had completed climate adaptation plans; four states were in the process of writing their plans; and seven states had made recommendations to create state-wide adaptation plans.[37]

In addition to formal adaptation plans, numerous states have created sector-specific plans that consider long-term climate change (Figure 28.1). For example, at least 16 states have biodiversity conservation plans that focus on preparing for long-term changes in climate.[38] In addition to planning, some states have created legislation and/or programs that are either directly or indirectly targeted at reducing climate vulnerabilities (Table 28.2).

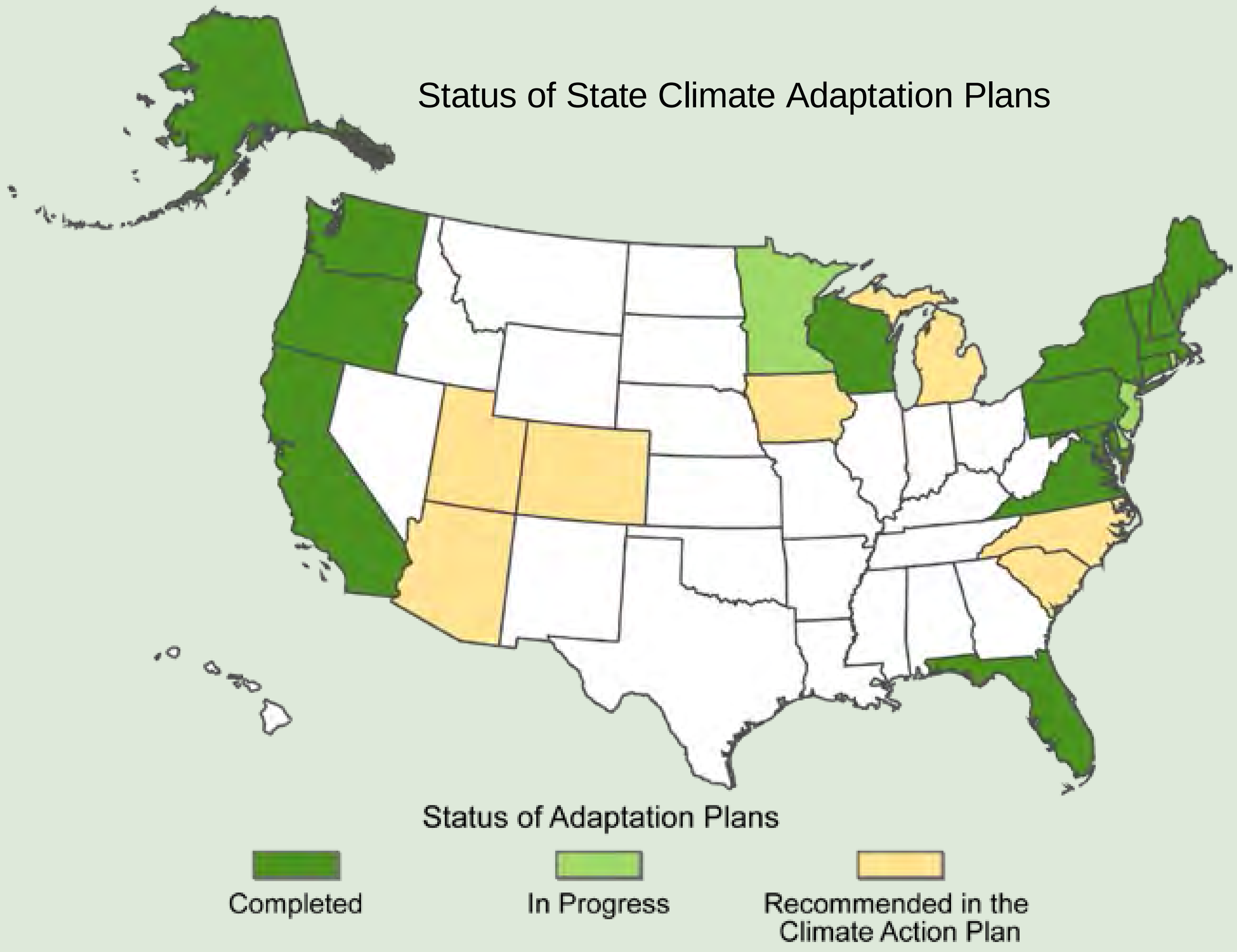

Figure 28.1. Status of State Climate Adaptation Plans. (Figure source: redrawn from C2ES 2013[37]).

Table 28.2. Examples of State-Level Adaptation Activities*

State	Adaptation Action
Alaska	Alaska Climate Change Impact Mitigation Program provides funds for hazard impact assessments to evaluate climate change related impacts, such as coastal erosion and thawing permafrost.[39]
California	Building standards mandating energy and water efficiency savings, advancing both adaptation and mitigation; State Adaptation Plan calls for 20% reduction in per capita water use.[40]
Florida	Law supporting low water use landscaping techniques.[41]
Hawaii	Water code that calls for integrated management, preservation, and enhancement of natural systems.[42]
Kentucky	*Action Plan to Respond to Climate Change in Kentucky: A Strategy of Resilience,* which identifies six goals to protect ecosystems and species in a changing climate.[43]
Louisiana	*Comprehensive Master Plan for a Sustainable Coast 2012* includes both protection and restoration activities addressing land loss from sea level rise, subsidence, and other factors over the next 50 years.[44]
Maine	The *Maine Sand Dune Rules* require that structures greater than 2,500 square feet be set back at a distance that is calculated based on the future shoreline position and considering two feet of sea level rise over the next 100 years.[45]
Maryland	Passed *Living Shorelines Act* to reduce hardened shorelines throughout the state;[46] passed "Building Resilience to Climate Change" policy which establishes practices and procedures related to facility siting and design, new land investments, habitat restoration, government operations, research and monitoring, resource planning, and advocacy.
Montana	Maintains a statewide climate change website to help stakeholders access relevant and timely climate information, tools, and resources.
New Mexico	The Active Water Resource Management program allows for temporary water rights changes in real time in case of drought.[47]
Pennsylvania	Enacted polices to encourage the use of green infrastructure and ecosystem-based approaches for managing storm water and flooding.[9]
Rhode Island	Requires public agencies considering land-use applications to accommodate a 3- to 5-foot rise in sea level.
Texas	Coordinated response to drought through National Integrated Drought Information System (NIDIS); RISAs (Southern Climate Impacts Planning Program [SCIPP], Climate Assessment for the Southwest [CLIMAS]); and state and private sector partners through anticipatory planning and preparedness (for example, implemented in 2011 drought).[48]

*This list contains selected examples of state-level adaptation activities and should not be considered all-inclusive.

Tribal Governments

Tribal governments have been particularly active in assessing and preparing for the impacts of climate change (see Ch. 12: Indigenous Peoples). For example:

- Adaptation planning in Point Hope, Alaska, emphasizes strategies for enhancing community health.[49]
- In Newtok, Alaska, the village council is leading a land-acquisition and planning effort to relocate the community, because climate change induced coastal erosion has destroyed essential infrastructure, making the current village site unsafe.[50]
- The Tulalip Tribes in Washington State are using traditional knowledge gleaned from elders, stories, and songs and combining this knowledge with downscaled climate data to inform decision-making.[51] Also in Washington State, the Swinomish Indian Tribal Community integrated climate change into decision-making in major sectors of the Swinomish Community, such as education, fisheries, social services, and human health.[52]
- The Haudenosaunee Confederacy in the northeastern U.S. is addressing climate impacts by preserving a native food base through seed-banking (Ch. 12: Indigenous Peoples).[51]

Local and Regional Governments

Most adaptation efforts to date have occurred at local and regional levels.[53,54,55,56,57] Primary mechanisms that local governments are using to prepare for climate change include land-use planning; provisions to protect infrastructure and ecosystems; regulations related to the design and construction of buildings, roads, and bridges; and emergency preparation, response, and recovery (Table 28.3).[9,45,56,58]

According to a recent survey of 298 U.S. local governments, 59% indicated they are engaged in some form of adaptation planning.[59] Local adaptation planning and actions are unfolding in municipalities of varying sizes and in diverse geographical areas. Communities such as Keene, New Hampshire; New York City, New York; King County, Washington; and Chicago, Illinois are vanguards in the creation of climate adaptation strategies.[9,11,60] In addition to local government action, regional agencies and regional aggregations of governments are becoming significant climate change adaptation actors.[8,57]

Table 28.3. Examples of Local and Regional Adaptation Activities*

Local or Regional Government	Adaptation Action
Satellite Beach, FL	Collaboration with the Indian River Lagoon National Estuary Program led to efforts to try to incorporate sea level rise projections and policies into the city's comprehensive growth management plan.[54]
Portland, OR	Updated the city code to require on-site stormwater management for new development and re-development. Provides a downspout disconnection program to help promote on-site stormwater management .[61]
Lewes, DE	In partnership with Delaware Sea Grant, ICLEI-Local Governments for Sustainability, the University of Delaware, and state and regional partners, the City of Lewes undertook a stakeholder-driven process to understand how climate adaptation could be integrated into the hazard mitigation planning process. Recommendations for integration and operational changes were adopted by the City Council and are currently being implemented.[62]
Groton, CT	Partnered with federal, state, regional, local, non-governmental, and academic partners through the EPA's Climate Ready Estuaries program to assess vulnerability to and devise solutions for sea level rise.[63]
San Diego Bay, CA	Five municipalities partnered with the port, the airport, and more than 30 organizations with direct interests in the Bay's future to develop the San Diego Bay Sea Level Rise Adaptation Strategy. The strategy identified key vulnerabilities for the Bay and adaptation actions that can be taken by individual agencies, as well as through regional collaboration.[9]
Chicago, IL	Through a number of development projects, the city has added 55 acres of permeable surfaces since 2008 and has more than four million square feet of green roofs planned or completed.[64]
King County, WA	Created King County Flood Control District in 2007 to address increased impacts from flooding through activities such as maintaining and repairing levees and revetments, acquiring repetitive loss properties, and improving countywide flood warnings.[65]
New York City, NY	Through a partnership with the Federal Emergency Management Agency (FEMA), the city is updating FEMA Flood Insurance Rate Maps based on more precise elevation data. The new maps will help stakeholders better understand their current flood risks and allow the city to more effectively plan for climate change.[66]
Southeast Florida Climate Change Compact	Joint commitment among Broward, Miami-Dade, Palm Beach, and Monroe Counties to partner in reducing heat-trapping gas emissions and adapting to climate impacts, including adaptation in transportation, water resources, natural resources, agriculture, and disaster risk reduction. Notable policies emerging from the Compact include regional collaboration to revise building codes and land development regulations to discourage new development or post-disaster redevelopment in vulnerable areas.[67]
Phoenix, AZ; Boston, MA; Philadelphia, PA; and New York, NY	Climate change impacts are being integrated into public health planning and implementation activities that include creating more community cooling centers, neighborhood watch programs, and reductions in the urban heat island effect.[9,68,69]
Boulder, CO; New York, NY; and Seattle, WA	Water utilities in these communities are using climate information to assess vulnerability and inform decision-making.[61]
City of Philadelphia	In 2006, the Philadelphia Water Department began a program to develop a green stormwater infrastructure, intended to convert more than one-third of the city's impervious land cover to "Greened Acres": green facilities, green streets, green open spaces, green homes, etc., along with stream corridor restoration and preservation.[5]

*This table includes select examples of local and regional adaptation activities and should not be considered all-inclusive.

There is no one-size-fits-all adaptation solution to the challenges of adapting to climate change impacts, as solutions will differ depending on context, local circumstance, and scale as well as on local culture and internal capacity.[9,31]

Non-governmental and Private Sector

Many non-governmental entities have been significant actors in the national effort to prepare for climate change by providing assistance that includes planning guidance, implementation tools, contextualized climate information, best practice exchange, and help with bridging the science-policy divide to a wide array of stakeholders (Table 28.4).[70,71] The Nature Conservancy, for example, established the Canyonlands Research Center in Monticello, Utah, to facilitate research and develop conservation applications for resource issues under the multi-stresses of climate change and land-use demands in the Colorado Plateau region.[72]

This one-acre stormwater wetland was constructed in Philadelphia to treat stormwater runoff in an effort to improve drinking water quality while minimizing the impacts of storm-related flows on natural ecosystems.

With regard to the private sector, evidence from organizations such as the Carbon Disclosure Project (CDP) and the Securities and Exchange Commission's (SEC) Climate Change 10-K Disclosure indicate that a growing number of companies are beginning to actively address risks from climate change (Table 28.5).[73] The World Business Council for Sustainable Development (WBCSD) and the Center for Climate and Energy Solutions (C2ES) have identified three types of risks driving private sector adaptation efforts, including risks to core operations, the value chain, and broader changes in the economy and infrastructure (see Figure 28.2).[74,75,76]

This analysis is supported by responses to the 2011 CDP, and suggests that companies are concerned about how changes in the climate will impact issues such as feedstock, water supply and quality, infrastructure, core operations, supply chains, and customers' ability to use (and their need for) services.[73]

Some companies are taking action to not only avoid risk, but to explore potential opportunities that may emerge in a changing climate, such as developing new products and services, developing or expanding existing consulting services, expanding into new operational territories, extending growing seasons and hours of operation, and responding to increased demand for existing products and services.[73,75,77,78]

Table 28.4. Examples of Non-governmental Adaptation Efforts and Services*

Types of Adaptation Efforts and Services	Examples of Organizations Providing Services
Adaptation planning assistance, including creation of guides, tools, and templates	Center for Climate Strategies, ICLEI-Local Governments for Sustainability, International Institute for Sustainable Development, Natural Resources Defense Council, The Nature Conservancy, World Resources Institute, World Wildlife Fund
Networking and best practice exchange	C40 Cities Climate Leadership Group, Adaptation Network, Center for Clean Air Policy, Climate Adaptation Knowledge Exchange, ICLEI-Local Governments for Sustainability, Institute for Sustainable Communities, Urban Sustainability Directors Network, World Business Council for Sustainable Development
Climate information providers	Union of Concerned Scientists, Urban Climate Change Research Network, Stockholm Environment Institute–U.S. Center
Policy, legal, and institutional support	Center for Climate and Energy Solutions (formerly Pew Center on Global Climate Change), Georgetown Climate Center
Aggregation of adaptation-pertinent information	Carbon Disclosure Project, Climate Adaptation Knowledge Exchange, Georgetown Climate Center

*This list contains examples of non-governmental organizations providing the identified services and should not be considered all-inclusive or a validation of actions claimed by the organizations.

Table 28.5. Examples of Private Sector Actions to Adapt to Climate Risks as Reported to the Carbon Disclosure Project*

Company	Sector	Climate Risk	Examples of Actions Undertaken
Coca-Cola Company	Consumer Staples	Changes in physical climate parameters; Changes in other climate-related developments	Coca-Cola is working around the world to replenish the water used in finished beverages by participating in locally relevant water projects that support communities and nature. Since 2005, the Coca-Cola system has engaged in more than 320 projects in 86 countries. The range of community projects includes watershed protection; expanding community drinking water and sanitation access; water for productive use, such as agricultural water efficiency; and education and awareness programs. (http://www.thecoca-colacompany.com/citizenship/conservation_partnership.html)
ConAgra Foods, Inc.	Consumer Staples	Company experienced weather-related sourcing challenges, such as delayed tomato harvesting due to unseasonably cool weather, and difficulty sourcing other vegetables due to above normal precipitation.	As part of its business continuity planning, ConAgra Foods has analyzed its supply risk to develop strategic partnerships with suppliers, minimize sole-sourced ingredients, and identify alternate suppliers and contract manufacturers to minimize production disruptions in the instance of an unexpected disruption in supply. (http://company.conagrafoods.com/phoenix.zhtml?c=202310&p=Policies_Environment)
Constellation Brands	Consumer Staples	Changes in physical climate parameters; Changes in other climate-related developments	Constellation has already taken adaptation actions, particularly in California where water availability is an issue, to manage or adapt to these risks. Constellation is working with numerous organizations to help fund industry-based research to determine potential climate change impacts on vineyard production.
Munich Re	Reinsurance	Changes in regulation; Changes in physical climate parameters; Changes in other climate-related developments	Since 2007, a Group-wide climate change strategy covering all aspects of climate change – for example, weather-related impacts, regulatory impacts, litigation and health risks, etc. – has supported their core corporate strategy. The strategy is based on five pillars: mitigation, adaptation, research, in-house carbon dioxide reduction, and advocacy. (http://www.munichre.com/en/group/focus/climate_change/default.aspx)
Pacific Gas and Electric Company (PG&E)	Utilities	Changes in regulation; changes in physical climate parameters; Changes in other climate-related developments	PG&E's adaptation strategies for potential increased electricity demand include expanded customer energy efficiency and demand response programs and improvements to its electric grid. PG&E is proactively tracking and evaluating the potential impacts of reductions to Sierra Nevada snowpack on its hydroelectric system and has developed adaptation strategies to minimize them. Strategies include maintaining higher winter carryover reservoir storage levels, reducing conveyance flows in canals and flumes in response to an increased portion of precipitation falling as rain, and reducing discretionary reservoir water releases during the late spring and summer. PG&E is also working with both the U.S. Geological Survey (USGS) and the California Department of Water Resources to begin using the USGS Precipitation-Runoff Modeling System (PRMS) watershed model, to help manage reservoirs on watersheds experiencing mountain snowpack loss. (http://www.pge.com/about/environment/commitment/)
SC Johnson & Son, Inc.	Household Products	Changes in physical climate parameters	SC Johnson is adjusting to the various physical risks that climate change imposes through a diversified supplier and global manufacturing base. In March 2009, SC Johnson announced a broad ingredient communication program. SC Johnson assesses risks along each ingredient's supply chain to ensure that the company is sourcing from a geographically diverse supplier base. In addition to evaluating product ingredients, SC Johnson has also diversified its operations around the world, allowing it to maintain business continuity in the face of a regional climate change related disruption. (http://www.scjohnson.com/en/commitment/overview.aspx)
Spectra Energy, Inc.	Energy	Changes in regulation; Changes in physical climate parameters; Changes in other climate-related developments	Spectra Energy uses a corporate-wide risk analysis framework to ensure the oversight and management of its four major risk categories: financial, strategic, operational, and legal risks. Physical risks posed by climate change fall within these categories and the company uses risk management committees to ensure that all material risks are identified, evaluated, and managed prior to financial approvals of major projects. (http://www.spectraenergy.com/Sustainability/)

* This list contains examples of private sector actions to adapt to climate risks as reported to the Carbon Disclosure Project and should not be considered all-inclusive or a validation of actions claimed by the organizations.

Effects of Climate Change on...

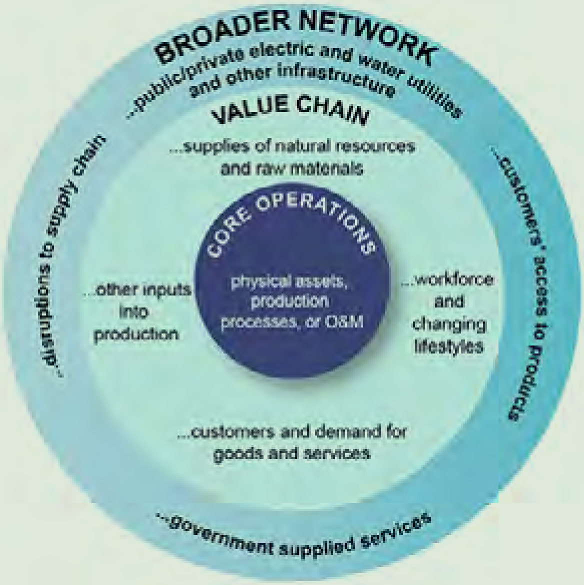

Figure 28.2. "Risk Disk" depicts three pathways by which risks posed by climate change can affect business, such as through core operations, the value chain, and broader changes in the economy and infrastructure. (Figure source: redrawn from C2ES 2008[74]).

Section 1: Adaptation Process

General patterns in adaptation processes are beginning to emerge, with similarities discernible across sectors, systems, and scales.[53,78,79]

Adaptation Process

Figure 28.3. Generalized Adaptation Process (Figure source: adapted from NRC 2010[11]).

This is not a stepwise or linear process; various stages can be occurring simultaneously, in a different order, or be omitted completely. However, as shown clockwise in Figure 28.3, the process generally involves characterizing vulnerability, developing options, implementing actions, monitoring outcomes, and reevaluating strategies. Each of these is described in more detail below.

Identifying and Understanding Risk, Vulnerabilities, and Opportunities

Most adaptation actions are currently in the initial phase, with many actors focusing on identifying the relevant climate risks and conducting current and future risk and vulnerability assessments of their assets and resources.[8,11,59,80,81,82] In 2011, only 13% of 298 U.S. municipalities surveyed had completed vulnerability or risk assessments, but 42% expected to complete an assessment in the future.[59] At least 21 state fish and wildlife agencies have undertaken climate vulnerability assessments or recently completed an assessment of a particular species, habitat, or both.[38] Multiple qualitative and quantitative methods are used to understand climate vulnerability and risk, including case studies and analogue analyses, scenario analyses, sensitivity analyses, monitoring of key species, and peer information sharing.[8,28,83,84]

Planning, Assessing, and Selecting Options

Once risks and vulnerabilities are understood, the next stage typically involves identifying, evaluating, and selecting options for responding to and managing existing and future changes in the climate.[28] Decision support planning methods and associated tools help to identify flexible and context-relevant adaptation activities for implementation.[11,79] Participatory approaches support the integration of stakeholder perspectives and context-specific information into decision-making.[85,86] This approach can include having community members and governing institutions work collectively to define the problem and design adaptation strategies that are robust while being sensitive to stakeholder values.[86,87] Moreover, regional collaboration has emerged as an effective strategy for defining common approaches to reducing potential threats, selecting metrics for tracking purposes, and creating governance structures to help navigate political challenges.[67,88] As discussed above, a number of government and other organizations have developed plans with identified adaptation options.

Common approaches to adaptation planning include "mainstreaming" or integrating climate adaptation into existing management plans (for example, hazard mitigation, ecosystem conservation, water management, public health, risk contingency, and energy) or developing stand-alone adaptation plans.[68,82,89,90]

Many frameworks, tools, and approaches have emerged to help decision-makers make decisions in light of both uncertainty and the need to achieve multiple societal goals.[7,79] Some of these, however, are specific to particular localities or resources, are not easy to use by the intended audiences, do not adequately evaluate tradeoffs, and require sophisticated knowledge of climate change.[91] In general, these approaches promote options that allow reversibility, preserve future options, can tolerate a variety of impacts, and are flexible, such that mid-course adjustments are possible.[32,92] Among these approaches are Robust Decision Making (RDM), Iterative Risk Management (IRM), Adaptive Management or Co-Management, Portfolio Management, and Scenario Planning (see Ch. 26: Decision Support for more on decision frameworks, processes, and tools).[7,11,28,54,93,94,95,96,97]

Implementation

There is little peer-reviewed literature on adaptation actions, or evaluations of their successes and failures.[11,36,81,98] Many of the documents submitted as part of this Third National Climate Assessment (NCA) process indicate that adaptation actions are being implemented for a variety of reasons. Often, these are undertaken with an aim toward reducing current vulnerabilities to hazards or extreme weather events, such as forest thinning and fuel treatments that reduce fire hazards in national forests or through the diversification of supply chain sourcing in the private sector.[72,73] Additionally, an increasing movement toward mainstreaming climate adaptation concerns into existing processes means that discerning unique climate adaptation activities will be a challenge.[82,99]

Monitoring and Evaluation

There is little literature evaluating the effectiveness of adaptation actions.[9,72,79,86] Evaluation and monitoring efforts, to date, have focused on the creation of process-based rather than outcome-based indicators.[86,90] A number of efforts are underway to create indicators related to climate adaptation,[27] including work by the National Climate Assessment and Development Advisory Committee Indicators Working Group[100] and the U.S. Environmental Protection Agency.[101] Part of monitoring should include accounting for costs of adaptation. To be sure, this may be difficult to account for because of challenges in attribution of climate events to climate change versus climate variability. A few studies summarize projected future costs of adaptation.[102,103]

Revise Strategies/Processes and Information Sharing

Uncertainty about future climate as well as population growth, economic development, response strategies, and other social and demographic issues can stymie climate adaptation activity.[95,104,105] Through iterative processes, however, stakeholders can regularly evaluate the appropriateness of planned and implemented activities and revise them as new information becomes available.[11,28,84] Additionally, the sharing of best practices and lessons learned can be pivotal means to advancing understanding and uptake of climate adaptation activity.[82,86] The use of established information-sharing networks, such as regional climate initiatives, are illustrations of the types of networks that have supported stakeholder adaptation activity to-date.[9,76,79,86]

Section 2: Barriers to Adaptation and Examples of Overcoming Barriers

Despite emerging recognition of the necessity of climate change adaptation, many barriers still impede efforts to build local, regional, and national-level resilience. Barriers are obstacles that can delay, divert, or temporarily block the adaptation process,[106] and include difficulties in using climate change projections for decision-making; lack of resources to begin and sustain adaptation efforts; lack of coordination and collaboration within and across political and natural system boundaries as well as within organizations; institutional constraints; lack of leadership; and divergent risk perceptions/cultures and values (Table 28.6).[11,20,107] Barriers are distinguished from physical or ecological limits to adaptation, such as physiological tolerance of species to changing climatic conditions that cannot be overcome (except with technology or some other physical intervention).[8,54,108]

Despite barriers, individuals within and across sectors and regions are organizing to collectively overcome barriers and adapt to climate change. In many cases, lessons learned from initial programs help inform future adaptation strategies. Figure 28.4 highlights ongoing climate adaptation activities that have overcome some of these barriers in different regions led

Table 28.6. Summary of Adaptation Barriers

Barrier	Specific Examples
Climate Change Information and Decision-Making References: [7,8,10,11,14,17,31,32,42,59,68,69,72,82,90,93,104,109,110,111,112]	• Uncertainty about future climate impacts and difficulty in interpreting the cause of individual weather events • Disconnect between information providers and information users • Fragmented, complex, and often confusing information • Lack of climate education for professionals and the public • Lack of usability and accessibility of existing information • Mismatch of decision-making timescales and future climate projections
Lack of Resources to Begin and Sustain Adaptation Efforts References: [8,13,42,51,54,59,81,82,111,112,113,114]	• Lack of financial resources / no dedicated funding • Limited staffing capacity • Underinvestment in human dimensions research
Fragmentation of Decision-Making References: [8,14,31,32,51,68,115,116]	• Lack of coordination within and across agencies, private companies, and non-governmental organizations • Uncoordinated and fragmented research efforts • Disjointed climate related information • Fragmented ecosystem and jurisdictional boundaries
Institutional Constraints References: [8,13,42,51,54,97,113,117,118,119]	• Lack of institutional flexibility • Rigid laws and regulations • No legal mandate to act • Use of historical data to inform future decisions • Restrictive management procedures • Lack of operational control or influence
Lack of Leadership References: [30,96,112,113,119,120,121]	• Lack of political leadership • Rigid and entrenched political structures • Polarization
Divergent Risk Perceptions, Cultures, and Values References: [51,71,82,116,117,120,122]	• Conflicting values/risk perceptions • Little integration of local knowledge, context, and needs with traditional scientific information • Cultural taboos and conflict with cultural beliefs • Resistance to change due to issues such as risk perception

by state, local, and private actors in the United States. It is not a comprehensive compilation of national adaptation activity, but is intended to identify some of the variety of adaptation efforts taking place across the country.

In addition, Section 4 of this chapter provides four in-depth case studies of climate adaptation strategies at different scales, with multiple stakeholders, and tackling different challenges. Each of these case studies highlights the different ways stakeholders are approaching adaptation.

- Through the creation of the National Integrated Drought Information System (NIDIS), the Federal Government, in partnership with the National Drought Mitigation Center (NDMC), states, tribes, universities, and others, has improved capacity to proactively manage and respond to drought-related risks and impacts through: 1) the provision of drought early warning information systems with local/regional input on extent, onset, and severity; 2) a web-based drought portal featuring the U.S. Drought Monitor and other visualization tools; 3) coordination of research in support and use of these systems; and 4) leveraging of existing partnerships, forecasting, and assessment programs.
- In the Colorado River Basin, water resource managers, government leaders, federal agencies, tribes, universities, nongovernmental organizations (NGOs), and the private sector are collaborating on strategies for managing water under a changing climate through partnerships like the Western Governors' Association (WGA) and WestFAST (Western Federal Agency Support Team).
- In Wisconsin, the Northern Institute of Applied Climate Science and the U.S. Forest Service, working with multiple partners, initiated a "Climate Change Response Framework" integrating climate-impacts science with forest management.
- In Cape Cod, Massachusetts, the U.S. Department of Transportation's Volpe Center worked with federal, regional, state, and local stakeholders to integrate climate change mitigation and adaptation considerations into existing and future transportation, land-use, coastal, and hazard-mitigation processes.

Continued

Figure 28.4. Adaptation Activity

1. The State of Hawai‘i, Office of Planning, in cooperation with university, private, state, and federal scientists and others, has drafted a framework for climate change adaptation that identifies sectors affected by climate change, and outlines a process for coordinated statewide adaptation planning.[123]

2. One of the priorities of the Hawai‘i State Plan is preserving water sources through forest conservation, as indicated in their “Rain Follows The Forest” report.[124]

3. New England Federal Partners is a multi-agency group formed to support the needs of the states, tribes, and communities of the New England Region and to facilitate and enable informed decision-making on issues pertaining to coastal and marine spatial planning, climate mitigation, and climate adaptation throughout the region.[125]

4. Philadelphia is greening its combined sewer infrastructure to protect rivers, reduce greenhouse gas emissions, improve air quality, and enhance adaptation to a changing climate.[126]

5. Keene, NH, developed a Comprehensive Master Plan that emphasizes fostering walkable, mixed-use neighborhoods by putting services, jobs, homes, arts and culture, and other community amenities within walking distance of each other. The plan also calls for sustainable site and building designs that use resources efficiently. These strategies were identified in the city’s 2007 Adaptation Plan as ways to build resilience while reducing greenhouse gas emissions.[127]

6. New York City has created a Green Infrastructure Plan and is committed to goals that include the construction of enough green infrastructure throughout the city to manage 10% of the runoff from impervious surfaces by 2030.[128]

7. Lewes, DE, undertook an intensive stakeholder process to integrate climate change into the city’s updated hazard mitigation plan.[62]

8. Local governments and tribes throughout Alaska, such as those in Homer, are planting native vegetation and changing the coastal surface, moving inland or away from rivers, and building riprap walls, seawalls or groins, which are shore-protection structures built perpendicular to the shoreline (see also: Ch. 22:Alaska; Ch. 12: Indigenous Peoples).[129]

9. Alaskan villages are physically being relocated because of climate impacts such as sea level rise and erosion; these include Newtok, Shishmaref, Kivalina, and dozens of other villages.[130]

10. Cedar Falls, Iowa, passed legislation in 2009 that includes a new floodplain ordinance that expands zoning restrictions from the 100-year floodplain to the 500-year floodplain, because this expanded floodplain zone better reflects the flood risks experienced by the city during the 2008 floods.[131]

11. In January 2011, the Michigan Department of Community Health (MDCH) released the *Michigan Climate and Health Adaptation Plan*, which has a goal of “preparing the public health system in Michigan to address the public health consequences of climate change in a coordinated manner.” In September 2010, MDCH received three years’ funding to implement this plan as part of the Climate-Ready States and Cities Initiative of CDC.[132]

12. Chicago was one of the first cities to officially integrate climate adaptation into a citywide climate adaptation plan. Since its release, a number of strategies have been implemented to help the city manage heat, protect forests, and enhance green design, such as their work on green roofs.[64]

13. Grand Rapids, MI, recently released a sustainability plan that integrates future climate projections to ensure that the economic, environmental, and social strategies embraced are appropriate for today as well as the future.[133]

14. Tulsa, OK, has a three-pronged approach to reducing flooding and managing stormwater: a) prevent new problems by looking ahead and avoiding future downstream problems from new development (for example, requiring on-site stormwater detention); b) correct existing problems and learn from disasters to reduce future disasters (for example, through watershed management and the acquisition and relocation of buildings in flood-prone areas); and c) act to enhance the safety, environment, and quality of life of the community through public awareness, an increase in stormwater quality, and emergency management.[134]

15. Firewise Communities USA is a nationwide program of the National Fire Protection Association and is co-sponsored by USDA Forest Service, DOI, and the National Association of State Foresters. According to the Texas Forest Service, there are more than 20 recognized Texas Firewise Communities. The Texas Forest Service works closely with communities to help them to reach Firewise Community status and offers a variety of awareness, educational, informational, and capacity-building efforts, such as *Texas Wildscapes*, a program that assists in choosing less fire-friendly plants.[135]

Continued ▼

16. After the heavy rainfall events of 2004 that resulted in significant erosion on his farms, Dan Gillespie, a farmer with the Natural Resources Conservation Service in Norfolk, NE, began experimenting with adding cover crops to the no-till process. It worked so well in reducing erosion and increasing crop yields that he is now sharing his experience with other farmers. (http://www.lenrd.org/projects-programs/; http://www.notill.org/)[136]

17. Point Reyes National Seashore is preparing for climate change by removing two dams that are barriers to water flow and fish migration. This change restores ecological continuity for anadromous fish (those that migrate from the sea to fresh water to spawn), creating a more resilient ecosystem.[137]

18. Western Adaptation Alliance is a group of eleven cities in five states in the Intermountain West that share lessons learned in adaptation planning, develop strategic thinking that can be applied to specific community plans, and join together to generate funds to support capacity building, adaptation planning, and vulnerability assessment.[138]

19. Navajo Nation used information on likely changes in future climate to help inform their drought contingency plan.[139]

20. California Department of Health and the Natural Resources Defense Council collaborated to create the *Public Health Impacts of Climate Change in California: Community Vulnerability Assessment and Adaptation Strategies* report, which is being used to inform public health preparedness activities in the state.[140]

21. State of Idaho successfully integrated climate adaptation into the state's Wildlife Management Plan. (http://fishandgame.idaho.gov/public/wildlife/cwcs/)[8]

22. The Rising Tides Competition was held in 2009 by the San Francisco Bay Conservation and Development Commission to elicit ideas for how the Bay could respond to sea level rise.[141]

23. Flagstaff, Arizona, created a resilience strategy and passed a resilience policy, as opposed to a formal adaptation plan, as a means to institutionalize adaptation efforts in city government operations.[142]

24. The Olympic National Forest and Olympic National Park were sites of case studies looking at how to adapt management of federal lands to climate change. Sensitivity assessments, review of management activities and constraints, and adaptation workshops in the areas of hydrology and roads, fish, vegetation, and wildlife were all components of the case study process.[143]

25. King County Flood Control District was reformed to merge multiple flood management zones into a single county entity for funding and policy oversight for projects and programs – partly in anticipation of increased stormwater flows due to climate change.[144]

26. The Water Utilities Climate Alliance has been working with member water utilities to ensure that future weather and climate considerations are integrated into short- and long-term water management planning. (http://www.wucaonline.org/html/)[90]

27. Seattle's RainWatch program uses an early warning precipitation forecasting tool to help inform decisions about issues such as drainage operations. (http://www.atmos.washington.edu/SPU/)[19]

28. City of Portland and Multnomah County created a Climate Action Plan that includes indicators to help them gauge progress in planning and implementing adaptation actions.[145]

29. In 2010, the state of Louisiana launched a $10 million program to assist communities that had been affected by Hurricanes Gustav and Ike in becoming more resilient to future environmental problems. Twenty-nine communities from around the state were awarded resiliency development funds. The Coastal Sustainability Studio at Louisiana State University started working in 2012 with all 29 funded communities, as well as many that did not receive funds, to develop peer-learning networks, develop best practices, build capacity to implement plans, and develop planning tools and a user-inspired and useful website to increase community resiliency in the state.[146]

30. U.S. Fish and Wildlife Service and The Nature Conservancy are cooperating in a pilot adaptation project to address erosion and saltwater intrusion, among other issues, in the Alligator River Refuge. This project incorporates multiple agencies, native knowledge, community involvement, local economics, and technical precision.[147]

31. North and South Carolina are actively working to revise their state wildlife strategies to include climate adaptation.[82]

32. The Southeast Florida Climate Change Compact is a collaboration of the four southernmost counties in Florida (Monroe, Broward, Palm Springs, and Miami-Dade) focusing on enhancing regional resilience to climate change and reducing regional greenhouse gas emissions.[67]

Section 3: Next Steps

Adaptation to climate change is in a nascent stage. The Federal Government is beginning to develop institutions and practices necessary to cope with climate change, including efforts such as regional climate centers within the U.S. Department of Agriculture, the National Oceanic and Atmospheric Administration (a division of the U.S. Department of Commerce), and the U.S. Department of the Interior. While the Federal Government provides financial assistance in federally-declared disasters, it is also enabling and facilitating early adaptation within states, regions, local communities, and the public and private sectors.[11] The approaches include working to limit current institutional constraints to effective adaptation, funding pilot projects, providing useful and usable adaptation information – including disseminating best practices and helping develop tools and techniques to evaluate successful adaptation.

Despite emerging efforts, the pace and extent of adaptation activities are not proportional to the risks to people, property, infrastructure, and ecosystems from climate change; important opportunities available during the normal course of planning and management of resources are also being overlooked. A number of state and local governments are engaging in adaptation planning, but most have not taken action to implement the plans.[107] Some companies in the private sector and numerous non-governmental organizations have also taken early action, particularly in capitalizing on the opportunities associated with facilitating adaptive actions. Actions and collaborations have occurred across all scales. At the same time, barriers to effective implementation continue to exist (see Section 2).

One of the overarching key areas of focus for global change research is enabling research and development to advance adaptation across scales, sectors, and disciplines. This includes social science research for overcoming the barriers identified in Section 2, such as strategies that foster coordination, better communication, and knowledge sharing amongst fragmented governing structures and stakeholders. Research on the kinds of information that users desire and how to deliver that information in contextually appropriate ways and research on decision-making in light of uncertainty about climate change and other considerations will be equally important. In addition to these areas, emerging areas of emphasis include:

- Costs and Benefits of Adaptation: Methodologies to evaluate the relevant costs of adaptation options, as well as the costs of inaction, need to be developed.[6,102]

- A Compendium of Adaptation Practices: A central and streamlined database of adaptation options implemented at different scales in space and time is needed. Information on the adaptation actions, how effective they were, what they cost, and how monitoring and evaluation were conducted should be part of the aggregated information.[11,20,31]

- Adaptation and Mitigation Interactions: Research and analysis on the growing and competing demands for land, water, and energy and how mitigation actions could affect adaptation options, and vice versa.[4,27,81,148]

- Critical Adaptation Thresholds: Research to identify critical thresholds beyond which social and/or ecological systems are unable to adapt to climate change. This should include analyzing historical and geological records to develop models of "breakpoints".[2,31,149]

- Adaptation to Extreme Events: Research on preparedness and response to extreme events such as droughts, floods, intense storms, and heat waves in order to protect people, ecosystems, and infrastructure. Increased attention must be paid to how extreme events and variability may change as climate change proceeds, and how that affects adaptation actions.[11,150]

Effective adaptation will require ongoing, flexible, transparent, inclusive, and iterative decision-making processes, collaboration across scales of government and sectors, and the continual exchange of best practices and lessons learned. All stakeholders have a critical role to play in ensuring the preparedness of our society to extreme events and long-term changes in climate.

Section 4: Case Studies

Illustrative Case One: National Integrated Drought Information System

NIDIS (National Integrated Drought Information System), originally proposed by the Western Governors' Association (WGA) and established by Congress in 2006,[151] is a federally-created entity that improves the nation's capacity to proactively manage drought-related risks across sectors, regions, and jurisdictions. It was created by Congress to "enable the Nation to move from a reactive to a more proactive approach to managing drought risks and impacts." NIDIS has successfully brought together government partners and research organizations to advance a warning system for drought-sensitive areas.

The creation of NIDIS involved many years of development and coordination among federal, state, local, regional, and tribal partners with the help of Governors' associations and Senate and Congressional leaders. NIDIS provides: 1) drought early warning information systems with regional detail concerning onset and severity; 2) a web-based portal (www.drought.gov);

3) coordination of federal research in support of and use of these systems; and 4) leveraging of existing partnerships and of forecasting and assessment programs. NIDIS currently supports work on water supply and demand, wildfire risk assessment and management, and agriculture. Regional drought early warning system pilot projects have been established to illustrate the benefits of improved knowledge management, improved use of existing and new information products, and coordination and capacity development for early warning systems. These prototype systems are in the Upper Colorado Basin, the Apalachicola-Chattahoochee-Flint River Basin in the Southeast, the Four Corners region in the Southwest, and California. The NIDIS Outlook in the Upper Colorado Basin provides early warning information every week, for example, that is utilized by a variety of users from federal agencies, water resource management, and the recreation industry.

The Western Governors' Association, the U.S. Congress, and others have formally acknowledged that NIDIS provides a successful example of achieving effective federal-state partnerships by engaging both leadership and the public, and establishing an authoritative basis for integrating monitoring and research to support risk management. Some of NIDIS's keys to success include:

- Usable Technology and Information for Decision Support: The production of the U.S. Drought Monitor map, which integrates multiple indicators and indices from many data sources, was developed before NIDIS was established and has become a useful visual decision support tool for monitoring and characterizing drought onset, severity, and persistence. NIDIS has engaged regional and local experts in refining the regional details of this national product and in "ground truthing" maps via email discussions and webinars (Figure 28.5).

- Financial Assistance: Federal funding was allocated to NOAA specifically for NIDIS, but leveraged in kind by other agencies and partners.

- Institutional/Partnerships: Effective collaborations, partnerships, and coordination with NOAA, WGA, USDA, DOI, and USGS as well as local, regional, state, and tribal partners and with the National Drought Mitigation Center at the University of Nebraska, Lincoln, have led to multi-institutional "buy-in."

- Institutional/Policy: The NIDIS Act was oriented toward the improvement of coordination across federal agencies and with regional organizations, universities, and states. It focused on the application of technology, including the Internet, and on impact assessments for decision support. A key aspect of NIDIS is the development of an ongoing regional outlook forum based on the above information to build awareness of the drought hazard and to embed information in planning and practice (in partnership with the National Drought Mitigation Center, the Regional Integrated Sciences and Assessments (RISA), and other research-based boundary organizations) to reduce risks and impacts associated with drought**.**

- Leadership and Champions: NIDIS supporters worked at all levels over more than two decades (1990s and 2000s) to establish the NIDIS Act, including political groups (WGA, Southern Governors' Association, National Governors Association, and U.S. Senators and Representatives), scientific leaders, and federal agencies (NOAA, USDA, DOI).

- Risk Perceptions: Whereas drought had been considered primarily a western issue in previous decades, drought is now regularly affecting the southern, southeastern, and northeastern parts of the country and response strategies are needed. During the 2012 drought, more than 63% of the contiguous U.S. by the end of July was classified as experiencing moderate to exceptional drought, and more than 3,200 heat records were broken in June 2012 alone.[152]

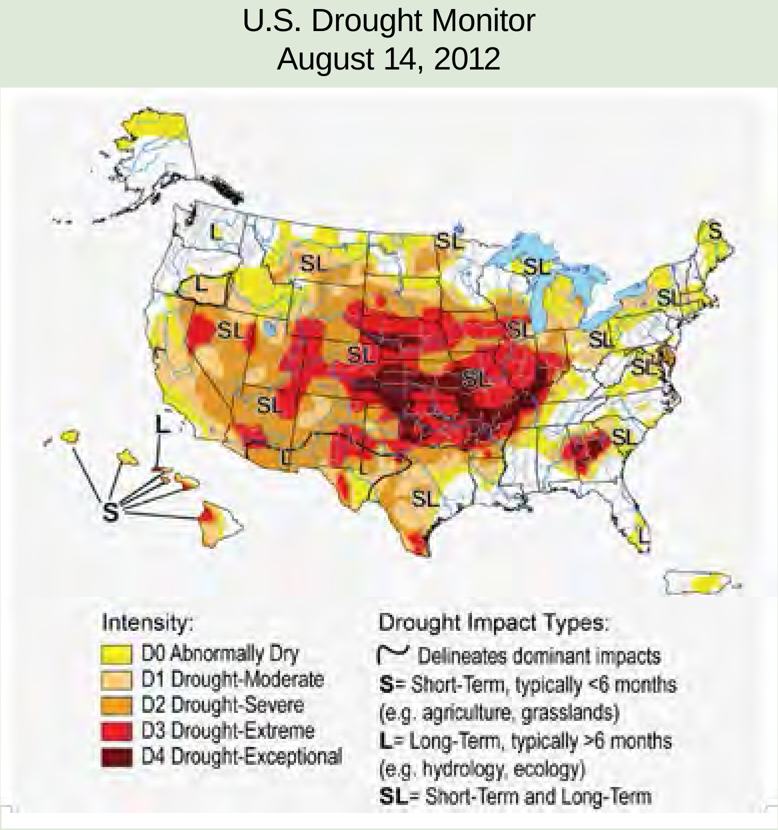

Figure 28.5. U.S. Drought Monitor Map accessed on August 20, 2012. The U.S. Drought Monitor is produced in partnership between the national Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC-UNL.

Illustrative Case Two: Adaptive Governance in the Colorado River Basin

The Colorado River supplies water and valuable ecosystem services to 33 million people and is vulnerable to climate change because of decreases in mountain snowpack and water availability, increased competition among water users, fires, drought, invasive species, and extended extreme heat events, among other threats.[13,153] The 1922 Colorado River Compact, which allocates water among seven U.S. states and Mexico, was agreed upon in a particularly wet time period;[154] thus the river water is already over-allocated for current conditions. Given the likelihood of having less water because of climate change, resource managers and government leaders are increasingly recognizing that water must be managed with flexibility to respond to the projected impacts and the range of possible future climates (see Ch. 2: Our Changing Climate; Ch. 3: Water).[13,155] Multiple actors across multiple disciplines, scales of governance (including tribal, local, state, and federal), non-governmental organizations, and the private sector are organizing and working together to address these concerns and the relationship between climate and other stresses in the basin.

The Western Governors' Association (WGA) spearheaded adaptation efforts to enable federal, state, tribal, local, and private sector partners to address a range of issues, including climate change.[13,155,156] For example, the Western Federal Agency Support Team (WestFAST), which was established in 2008, created a partnership between the Western States Water Council (WSWC) and 11 federal agencies with water management responsibilities in the western United States. The agencies created a work plan in 2011 to address three key areas: 1) climate change; 2) water availability, water use, and water reuse; and 3) water quality. To date they have produced the WestFAST Water-Climate Change Program Inventory, the Federal Agency Summary, and a Water Availability Studies Inventory (http://www.westgov.org/wswc/WestFAST.htm).

The WSWC and the USACE produced the Western States Watershed Study (WSWS), which demonstrated how federal agencies could work collaboratively with western states on planning activities.[157] In 2009, the WGA also adopted a policy resolution titled "Supporting the Integration of Climate Change Adaptation Science in the West" that created a Climate Adaptation Work Group composed of western state experts in air quality, forest management, water resources, and wildlife management. Other important adaptation actions were the SECURE Water Act in 2009, the Reclamation Colorado River Basin water supply and demand study, and the creation of NIDIS to support stakeholders in coping with drought.[151,158]

Illustrative Case Three: Climate Change Adaptation in Forests

Northern Wisconsin's climate has warmed over the past 50 years, and windstorms, wildfires, insect outbreaks, and floods are projected to become more frequent in this century.[160] The resulting impacts on forests, combined with fragmented and complex forest ownership, create management challenges that extend across ownership boundaries, creating the need for a multi-stakeholder planning process.[161]

To address these concerns, the Northern Institute of Applied Climate Science, the USDA's Forest Service, and many other partners initiated the Climate Change Response Framework to incorporate scientific research on climate change impacts into on-the-ground management. Originally developed as a pilot project for all-lands conservation in northern Wisconsin, it has expanded to cover three ecological regions (Northwoods [Figure 28.6], Central Hardwoods, and Central Appalachians) across eight states in the Midwest and Northeast. The Framework uses a collaborative and iterative approach to provide information and resources to forest owners and managers across a variety of private and public organizations. Several products were developed through the Framework in northern Wisconsin:

Figure 28.6. Northwoods Climate Change Response Framework Region (Figure Source: USDA Forest Service 2012[159]).

1. Vulnerability and mitigation assessments summarized the observed and projected changes in the northern Wisconsin climate, projected changes in forest composition and carbon stocks across a range of potential climates, and assessed related vulnerabilities of forest ecosystems in northern Wisconsin.[160]

2. Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers[162] was developed to help managers identify management tactics that facilitate adaptation. A "menu" of adaptation strategies and approaches for planning, implementing, and monitoring adaptation activities was synthesized into an adaptation workbook from a broad set of literature and refined based on feedback from regional scientists and managers.[163]

3. A series of adaptation demonstrations was initiated to showcase ground-level implementation. The Framework and adaptation workbook provide a common process shared by diverse landowners and a formal network that supports

cross-boundary discussion about different management objectives, ecosystems, and associated adaptation tactics.

From the beginning, the Framework has taken an adaptive management approach in its adaptation planning and projects. Lessons learned include:

- Define the purpose and scope of the Framework and its components early, but allow for refinement to take advantage of new opportunities.
- Begin projects with a synthesis of existing information to avoid duplicating efforts.
- Plan for the extra time necessary to implement true collaboration.
- Carefully match the skills, commitment, and capacity of people and organizations to project tasks.
- Maintain an atmosphere of trust, positivity, and sense of adventure, rather than dwelling on failures.
- Acknowledge and work with uncertainty, rather than submit to "uncertainty paralysis."
- Recognize the necessity of effective communication among people with different goals, disciplinary backgrounds, vocabulary, and perspectives on uncertainty.
- Integrate the ecological and socioeconomic dimensions early by emphasizing the many ways that communities value and depend on forests.
- Use technology to increase efficiency of internal communication and collaboration, as well as outreach.

The Framework brings scientists and land managers together to assess the vulnerability of ecosystems based on scientific information and experience in order to plan adaptation actions that meet management goals. On-the-ground implementation has just begun, and an increased focus on demonstrations, monitoring, and evaluation will inform future adaptation efforts.

Illustrative Case Four: Transportation, Land Use, and Climate Change – Integrating Climate Adaptation and Mitigation in Cape Cod, Massachusetts

Cape Cod, Massachusetts, a region of scenic beauty and environmental significance, is currently affected by sea level rise, coastal erosion, and localized flooding – impacts that are likely to be exacerbated by climate change.[164,165] To address these concerns and help meet the state's greenhouse gas (GHG) reduction target (25% reduction based on 1990 levels by 2020), the U.S. Department of Transportation's Volpe Center worked with federal, regional, state, and local stakeholders to integrate climate change into existing and future transportation, land-use, coastal zone, and hazard mitigation planning through an initiative called the Transportation, Land Use, and Climate Change Pilot Project.[164,166]

The process was initiated through an expert elicitation held in mid-2010 to identify areas on Cape Cod that are or could potentially be vulnerable to sea level rise, flooding, and erosion. The Volpe Center then used a geographic information system (GIS) software tool to develop and evaluate a series of transportation and land-use scenarios for the Cape under future development projections.[165,167] All scenarios were evaluated against a series of criteria that included: 1) reduction in vehicle miles traveled; 2) reduced heat-trapping gas emissions; 3) reduction in transportation energy use; 4) preservation of natural/existing ecosystems; 5) reduction in percentage of new population in areas identified as vulnerable to climate change impacts; and 6) increased regional accessibility to transportation.[164]

Once the preliminary scenarios were developed, a workshop was convened in which community and transportation planners, environmental managers, and Cape Cod National Seashore stakeholders selected areas for development and transit improvements to accommodate new growth while meeting the goals of reduced heat-trapping gas emissions, increased resilience to climate change, and the conservation of natural systems.[165] Through interactive visualization tools, participants were able to see in real-time the impacts of their siting decisions, allowing them to evaluate synergies and potential tradeoffs of their choices and to highlight areas where conflict could or already does exist, such as increasing density of development in areas already or likely to be vulnerable to climate change.[168] As a result, the stakeholders developed a refined transportation and land-use scenario that will support the region's long-range transportation planning as well as other local, regional, and state plans. This updated scenario identifies strategies that have climate adaptation and mitigation value, helping to ensure that the region simultaneously reduces its heat-trapping gas footprint while building resilience to existing and future changes in climate.[164,165] The overall success of the pilot project stemmed from the intensive stakeholder interaction at each phase of the project (design, implementation, and evaluation).

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the process were bi-weekly technical discussions held from October 2011 to June 2012 via teleconference that focused on collaborative review and summary of all technical inputs relevant to adaptation (130+) as well as additional published literature, the iterative development of key messages, and the final drafting of the chapter. An in-person meeting was held in Washington, D.C., in June 2012. Meeting discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each key message. Consensus was reached on all key messages and supporting text.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Substantial adaptation planning is occurring in the public and private sectors and at all levels of government; however, few measures have been implemented and those that have appear to be incremental changes.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications indicate that a growing number of sectors, governments at all scales, and private and non-governmental actors are starting to undertake adaptation activity.[9,13] Much of this activity is focused on planning with little literature documenting implementation of activities.[8,11,82] Supporting this statement is also plentiful literature that profiles barriers or constraints that are impeding the advancement of adaptation activity across sectors, scales, and regions.[42,68]

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

KEY MESSAGE #2 TRACEABLE ACCOUNT

Barriers to implementation of adaptation include limited funding, policy and legal impediments, and difficulty in anticipating climate-related changes at local scales.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input. A significant quantity of reviewed literature profiles barriers or constraints that are impeding the advancement of adaptation activity across sectors, scales, and regions.[11,20,42,68]

Numerous peer-reviewed documents describe adaptation barriers (see Table 28.6). Moreover, additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

KEY MESSAGE #3 TRACEABLE ACCOUNT

There is no "one-size fits all" adaptation, but there are similarities in approaches across regions and sectors. Sharing best practices, learning by doing, and iterative and collaborative processes including stakeholder involvement, can help support progress.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Literature submitted for this assessment, as well as additional literature reviewed by the author team, fully supports the concept that adaptations will ultimately need to be selected for their local applicability based on impacts, timing, political structure, finances, and other criteria.[11,90] Similarities do exist in the types of adaptation being implemented, although nuanced differences do make most adaptation uniquely appropriate for the specific implementer. The selection of locally and context-appropriate adaptations is enhanced by iterative and collaborative processes in which stakeholders directly engage with decision-makers and information providers.[11,20,28] While there are no "one-size fits all" adaptation strategies, evidence to date supports the message that the sharing of best practices and lessons learned are greatly aiding in adaptation progress across sectors, systems, and governance systems.[82,86]

Additional citations are used in the text of the chapter to substantiate this key message.

NEW INFORMATION AND REMAINING UNCERTAINTIES

n/a

ASSESSMENT OF CONFIDENCE BASED ON EVIDENCE

n/a

KEY MESSAGE #4 TRACEABLE ACCOUNT

Climate change adaptation actions often fulfill other societal goals, such as sustainable development, disaster risk reduction, or improvements in quality of life, and can therefore be incorporated into existing decision-making processes.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Literature submitted for this assessment, as well as additional literature reviewed by the author team, supports the message that a significant amount of activity that has climate adaptation value is initiated for reasons other than climate preparedness and/or has other co-benefits in addition to increasing preparedness to climate and weather impacts.[11,20,82,86,116] In recognition of this and other factors, a movement has emerged encouraging the integration of climate change considerations into existing decision-making and planning processes (i.e., mainstreaming).[5,11,40] The case studies discussed in the chapter amplify this point.

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

KEY MESSAGE #5 TRACEABLE ACCOUNT

Vulnerability to climate change is exacerbated by other stresses such as pollution, habitat fragmentation, and poverty. Adaptation to multiple stresses requires assessment of the composite threats as well as tradeoffs amongst costs, benefits, and risks of available options.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Climate change is only one of a multitude of stresses affecting social, environmental, and economic systems. Activity to date and literature profiling those activities support the need for climate adaptation activity to integrate the concerns of multiple stresses in decision-making and planning.[16,17,32] As evidenced by activities to date, integrating multiple stresses into climate adaptation decision-making and vice versa will require the assessment of tradeoffs amongst costs, benefits, the risks of available options, and the potential value of outcomes.[5,90,111]

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

KEY MESSAGE #6 TRACEABLE ACCOUNT

The effectiveness of climate change adaptation has seldom been evaluated, because actions have only recently been initiated and comprehensive evaluation metrics do not yet exist.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications indicate that no comprehensive adaptation evaluation metrics exist, meaning that no substantial body of literature or guidance materials exist on how to thoroughly evaluate the success of adaptation activities.[11,81,110] This is an emerging area of research. A challenge of creating adaptation evaluation metrics is the growing interest in mainstreaming; this means that separating out adaptation activities from other activities could prove difficult.

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

Climate Change Impacts in the United States

CHAPTER 29
RESEARCH NEEDS FOR CLIMATE AND GLOBAL CHANGE ASSESSMENTS

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On the Web: http://nca2014.globalchange.gov/report/response-strategies/research-needs

29 RESEARCH NEEDS FOR CLIMATE AND GLOBAL CHANGE ASSESSMENTS

Overview

This chapter identifies key areas of research to provide foundational understanding and advance climate assessments. Many of these research topics overlap with those needed for advancing scientific understanding of climate and its impacts and for informing a broader range of relevant decisions.

The research areas and activities discussed in this chapter were identified during the development of the regional and sectoral technical input reports, from the contributions of over 250 National Climate Assessment (NCA) chapter authors and experts, and from input from reviewers. The five high-level research goals, five foundational cross-cutting research capabilities, and more specific research elements described in this chapter also draw from a variety of previous reports and assessments. These lists are provided as recommendations to the Federal Government. Priority activities for global change research across 13 federal agencies are coordinated by the U.S. Global Change Research Program, which weighs all activities within the more than $2 billion annual climate science portfolio relative to one another, considering agency missions, priorities, and budgets.

The last National Climate Assessment report, released by the U.S. Global Change Research Program (USGCRP) in 2009, recommended research on: 1) climate change impacts on ecosystems, the economy, health, and the built environment; 2) projections of climate change and extreme events at local scales; 3) decision-relevant information on climate change and its impacts; 4) thresholds that could lead to abrupt changes in climate or ecosystems; 5) understanding the ways to reduce the rate and magnitude of climate change through mitigation; and 6) understanding how society can adapt to climate change.[1]

Some of these topics have received continued or increased attention in the last five years – such as ecosystem impacts, downscaled climate projections, and mitigation options – but the current assessment finds that significant knowledge gaps remain for all of the research priorities identified in 2009. This conclusion is reinforced by the findings of many subsequent reviews by the National Research Council (NRC) and others who have continued to identify these as priorities. For example, the NRC's *America's Climate Choices Panel on Advancing the Science of Climate Change and the Panel on Informing Effective Decisions and Actions*[2,3] highlighted several priorities that are relevant to climate assessments (see "Cross-Cutting Themes for the New Era of Climate Change Research Identified by America's Climate Choices"). These included the need for a more comprehensive, interdisciplinary, use-inspired, and integrated research enterprise that combines fundamental understanding of climate change and response choices, that improves understanding of human-environment systems; that supports effective adaptation and mitigation responses, and that provides better observing systems and projections. In recognition of fiscal limitations, it is clear that research agencies and partners will need to work together to leverage resources and ensure coordinated and collaborative approaches.

RESEARCH GOALS AND CROSS-CUTTING CAPABILITIES

Five Research Goals

- Improve understanding of the climate system and its drivers
- Improve understanding of climate impacts and vulnerability
- Increase understanding of adaptation pathways
- Identify the mitigation options that reduce the risk of longer-term climate change
- Improve decision support and integrated assessment

Five Foundational Cross-Cutting Research Capabilities

- Integrate natural and social science, engineering, and other disciplinary approaches
- Ensure availability of observations, monitoring, and infrastructure for critical data collection and analysis
- Build capacity for climate assessment through training, education, and workforce development
- Enhance the development and use of scenarios
- Promote international research and collaboration

CROSS-CUTTING THEMES FOR THE NEW ERA OF CLIMATE CHANGE RESEARCH IDENTIFIED BY *AMERICA'S CLIMATE CHOICES*

Research to Improve Understanding of Human-Environment Systems

1. Climate forcings, feedbacks, responses, and thresholds in the Earth system
2. Climate-related human behaviors and institutions

Research to Support Effective Responses to Climate Change

3. Vulnerability and adaptation analyses of coupled human-environment systems
4. Research to support strategies for limiting climate change
5. Effective information and decision support systems

Research Tools and Approaches to Improve Both Understanding and Responses

6. Integrated climate observing systems
7. Improved projections, analyses, and assessments

Source: *America's Climate Choices, Advancing the Science of Climate Change, National Academy of Sciences 2010*, p. 92.[4]

The U.S. Global Change Research Program's 2012-2021 Strategic Plan[5] lists a number of strategic goals and objectives for advancing science, informing decisions, conducting sustained assessments, and communicating and educating about global change. The plan includes research priorities to understand Earth system components, their interactions, vulnerability and resilience; advance observations, modeling, and information management; and evaluate assessment processes and products.

This chapter focuses specifically on the research identified through the National Climate Assessment process as needed to improve climate assessments. It is not intended to cover the full range of goals and related research priorities of the USGCRP and other groups, but instead to focus on research that will improve ongoing assessments. Therefore, many USGCRP priorities for climate change and global change science more broadly are not reflected here. The chapter does, however, directly support the USGCRP Strategic Plan's sustained assessment activities (see "Goal 3 of the USGCRP Strategic Plan").

This chapter is not intended to prescribe a specific research agenda but summarizes the research needs and gaps that emerged during development of this Third National Climate Assessment report that are relevant to the development of future USGCRP research plans.

During the development of this report, the authors were concerned that several important topics could not be comprehensively covered. In addition, several commenters noted the absence of these topics and felt that they were critical to consider in future reports. These include analyses of the economic costs of climate change impacts (and the associated benefits of mitigation and adaptation strategies); the implications of climate change for U.S. national security as a topic integrated with other regional and sectoral discussions; and the interactions of adaptation and mitigation options, including consideration of the co-benefits and potential unintended consequences of particular decisions.

GOAL 3 OF THE USGCRP STRATEGIC PLAN

Conduct Sustained Assessments: Build sustained assessment capacity that improves the Nation's ability to understand, anticipate, and respond to global change impacts and vulnerabilities.

The USGCRP will conduct and participate in national and international assessments to evaluate past, current, and likely future scenarios of global change and their impacts, as well as how effectively science is being used to support and inform the United States' response to change. The USGCRP will integrate emerging scientific understanding of the Earth system into assessments and identify critical gaps and limitations in scientific understanding. It will also build a standing capacity to conduct national assessments and support those at regional levels. The USGCRP will evaluate progress in responding to change and identify science and stakeholder needs for further progress. The program will use this regular assessment to inform its priorities.

Research Goals

Research Goal 1: Improve understanding of the climate system and its drivers

Research investments across a broad range of disciplines are critically important to building understanding of, and in some cases reducing uncertainties related to, the physical and human-induced processes that govern the evolution of the climate system. This assessment demonstrates the continued need for high quality data and observations, analysis of Earth system processes and changes, and modeling that increases understanding and projections of climate change across scales. Social science research is also essential to improved understanding and modeling of the drivers of climate change, such as energy use and land-use change, as well as understanding impacts (see Research Goal 2). Assessing a changing climate requires understanding the role of feedbacks, thresholds, extreme events, and abrupt changes and exploring a range of scenarios (see Cross-Cutting Research Capabilities section) that drive changes in the climate system.

This assessment reveals several research needs including:

- **Continue efforts to improve the understanding, modeling, and projections of climate changes,** especially at the regional scale, including driving forces of emissions and land-use change, changes in temperature, precipitation, soil moisture, runoff, groundwater, evapotranspiration, permafrost, ice and snow cover, sea level change, and ocean processes and chemistry;
- **Improve characterization of important sources of uncertainty, including feedbacks and possible thresholds in the climate system** associated with changes in clouds, land and sea ice, aerosols (tiny particles in the atmosphere), greenhouse gases, land use and land cover, emissions scenarios, and ocean dynamics;
- **Develop indicators that allow for timely reporting and enhanced public understanding** of climate changes and that allow anticipation and attribution of changes, including abrupt changes and extreme events in the context of a changing climate; and
- **Advance understanding of the interactions of climate change and natural variability** at multiple time scales, including seasonal to decadal changes (and consideration of climate oscillations including the El Niño Southern Oscillation, Pacific Decadal Oscillation, and the North Atlantic Oscillation), and extreme events (such as hurricanes, droughts, and floods).

Research Goal 2: Improve understanding of climate impacts and vulnerability

Assessing the implications of climate change for the U.S. relies not just on studies of the threats associated with changing weather patterns due to climate change and emerging chronic stresses such as sea level rise, but also on studies of who or what is exposed and sensitive to those threats, their underlying vulnerability, the associated costs, and adaptive capacity. The detailed sectoral and regional chapters of this assessment show that considerable progress has been made in understanding the extent to which natural and human systems in the U.S. are vulnerable to climate change and how these vulnerabilities combine with climatic trends and exposures to create impacts, but there is still a need to build capacity for assessing vulnerability.

This assessment suggests related research goals and activities including:

- **Maintain and enhance research and development of data collection and analyses to monitor and attribute ongoing and emerging climate impacts across the United States,** including changes in ecosystems, pests and pathogens, disaster losses, water resources, oceans, and social, urban, and economic systems. Priorities include ensuring enhanced geographic coverage of impacts research; the assessment of economic costs and benefits, as well as comparative studies of alternative response options; social science research focused on impacts; and the use of geospatial data systems;
- **Assess the impacts of climatic extremes, high-end temperature scenarios, and abrupt climate change** on ecosystems, health, food, water, energy, infrastructure, and other critical sectors, and improve modeling capabilities to better project and understand the vulnerability and resilience of human systems and ecosystems to climate change and other stresses such as land-use change and pollution;
- **Increase the understanding of how climate uncertainties combine with socioeconomic and ecological uncertainties** and identify improved ways to communicate the combined outcomes;
- **Develop measurement tools and valuation methods** for documenting the economic consequences of climate changes;
- **Expand climate impact analyses to focus on understudied but significant economic sectors** such as natural resources and energy development (for example, mining,

oil, gas, and timber); manufacturing; infrastructure, land development, and urban areas; finance and other services; retail; and human health and well-being; and

- **Investigate how climate impacts are affected by, or increase inequity in, patterns of vulnerability of particular population groups** within the U.S. and abroad (for example, children, the elderly, the poor, and natural resource dependent communities).

Research Goal 3: Increase understanding of adaptation pathways

This assessment and others, including the *America's Climate Choices Adapting to the Impacts of Climate Change* report[2] and Chapter 4 (on adaptation and mitigation options and responses) of the Intergovernmental Panel on Climate Change's (IPCC) AR4 Synthesis Report,[6] identifies a broad set of research needs for understanding and implementing adaptation. These include research on adaptation processes, adaptive capacity, adaptation option identification, implementation and evaluation, and adaptive management of risks and opportunities.

Important needs include research on the limits to, timing of, and tradeoffs in adaptation, and understanding of how adaptation interacts with mitigation activities, other stresses, and broader sustainability issues.

This assessment suggests research activities to:

- **Identify the best practices for adaptation planning, implementation, and evaluation** across federal, state, and local agencies, tribal entities, private firms, non-governmental organizations, and local communities. This requires the rigorous and comparative analysis of the effectiveness of iterative risk management, adaptation strategies and decision support tools (for example, in terms of stakeholder views, institutional structures including regional centers and multi-agency programs, cost/benefit, assessment against stated goals or social and ecological indicators, model validation, and use of relevant information, including traditional knowledge); and

- **Understand the institutional and behavioral barriers to adaptation and how to overcome them,** including revisions to legal codes, building and infrastructure standards, urban planning, and policy practices.

Research Goal 4: Identify the mitigation options that reduce the risk of longer-term climate change

The severity of climate change impacts in the U.S. and the need for adapting to them over the longer term will depend on the success of efforts to reduce or sequester heat-trapping greenhouse gas (GHG) emissions, particularly those associated with the burning of fossil fuels but also those associated with changes in land use. Managing the consequences of climate change over this century depends on reducing concentrations of greenhouse gases, including short-lived climate pollutants such as black carbon (soot).

While such efforts are necessarily worldwide, the U.S. produces a significant share of global greenhouse gases and can assist and influence other countries to reduce their emissions. Assessments can play a significant role in providing a better information base from which to analyze mitigation options.

Therefore, the mitigation section of this assessment (Ch. 27: Mitigation) noted the importance of research to understand and develop emission reductions through: 1) identifying climate and global change scenarios and their impacts; 2) providing a range of options for reducing the risks to climate and global change; and 3) developing options that allow joint mitigation-adaptation strategies, such as buildings that are more energy efficient and resilient to climate change impacts.

More generally, the *America's Climate Choices* report on *Limiting the Magnitude of Climate Change*[3] recommended that the U.S. promptly develop and implement appropriate strategies to reduce GHG emissions and identified important research needs, including the need to study the feasibility, costs, and consequences of different mitigation options. In addition, the report recommended research to support new technologies and the effective deployment of existing options, research into how best to monitor emissions and adherence to international policies, and research into how human behavior and institutions enable mitigation.[3]

This Third National Climate Assessment also suggests research activities to:

- **Develop information that supports analysis of new technologies** for energy production and use, carbon capture and storage, agricultural and land-use practices, and other technologies that could reduce or offset greenhouse gas emissions; research into the policy mechanisms that could be used to foster their development and implementation; analyses of the costs, benefits, tradeoffs, and synergies associated with different actions and combinations of actions; and improved understanding of the potential and risks of geoengineering;

- **Investigate the co-benefits, interactions, feedbacks, and tradeoffs between adaptation and mitigation** at the local and regional level, for example, in sectors such as agriculture, forestry, energy, health, and the built environment. This involves, as a priority, the assessment of the economics of impacts, mitigation, and adaptation;

- **Improve understanding of the effectiveness and timescales of mitigation measures** through deepened understanding of the relationship between the fate of human-induced and natural carbon emissions, uptake by the terrestrial biosphere and oceans, and atmospheric concentrations; and

- **Identify the critical social, cultural, institutional, economic, and behavioral processes that present barriers and opportunities for mitigation** at the federal and international levels and by individuals, state and local governments, and corporations.

Research Goal 5: Improve decision support and integrated assessment

For assessments to be useful to policy makers, they need to provide integrated results that can be used in decision-making. Research can develop tools that facilitate decision-making and the integration of knowledge.

Critical gaps in knowledge for decision support include the issues that affect the capacity of agencies, individuals, and communities to access and use the best available scientific information in support of decision-making, including the need to assess the ability of existing institutions, legal, and regulatory structures to respond to highly interdependent climate impacts. There are instances where policy barriers, institutional capacity or structure, or conflicting laws and regulations can create barriers to effective decisions. For instance, Chapter 12 (Indigenous Peoples) notes that there is no institutional framework for addressing village relocation in response to climate change in Alaska,[7] and Chapter 3 (Water) points out that existing water management institutions may be inadequate in the context of rapidly changing conditions. These instances point to research to evaluate whether the existing legal and regulatory structures, largely developed to address specific issues in isolation, can adequately respond to the highly interconnected issues associated with climate change. Decision support and integrated assessment also require research into the behavioral and other factors that influence individual decisions.

Assessments can benefit from research activities that:

- **Identify decision-maker needs** within regions and sectors, and support the development of research methods, tools, and information systems and models for managing carbon, establishing early warning systems, providing climate and drought information services, and analyzing the legal, regulatory, and policy approaches that support adaptation and mitigation efforts in the context of a changing climate;

- **Develop tools to support risk-based decision processes**, including tools to identify risk management information needs, develop transferable vulnerability assessment techniques, and evaluate alternative adaptation options. In addition, tools are needed to improve understanding of consumption patterns and environmental consequences; effective resource management institutions; iterative risk management strategies; and social learning, cognition, and adaptive processes;

- **Improve, fill gaps, and enhance research efforts to evaluate the effectiveness, costs, and benefits of mitigation and adaptation actions,** including economic and non-economic metrics that evaluate the costs of action, inaction, and residual impacts. Focus is also needed on the development of methods and baseline information supporting evaluation of completed and ongoing adaptation, mitigation, and assessment efforts that will foster adaptive learning; and

- **Develop, test and, expand integrated assessment models** that link decisions about emissions with impacts under different development pathways and ways to categorize uncertainties in the supporting data.

Foundational Cross-Cutting Research Capabilities to Support Future Climate Assessments

This assessment identifies a set of five foundational cross-cutting research capabilities that are essential for advancing our ability to continue to conduct climate and global change assessments and for addressing the five research goals.

1. Integrate natural and social sciences, engineering, and other disciplinary approaches

Continued advances in comprehensive and useful climate assessments will rely on additional interdisciplinary research. Understanding of the coupled human-environment system is enriched by combining research from natural and social sciences with research and experience from the engineering, law, and business professions.

Because human activities and decisions are influencing many Earth system processes, models and observations of natural and social changes at planetary, regional, and local scales are needed to understand how climate is changing, its impacts on people and environments, and how human responses feedback on the Earth system.

Building experienced interdisciplinary research teams that are able to understand each other's theories, methods, and language as well as the needs of stakeholders will allow for more rapid and effective assessments.

Interdisciplinary research is needed, for example, to:

- Understand how hydrological drivers of water supply interact with changing patterns of water demand and evolving water management practices to increase risks of drought, or influence the effectiveness of adaptation and mitigation options;
- Understand climate change in the context of multiple stresses on Earth, ecological, and human systems;
- Bring together economic and quantitative assessment of climate impacts and policies with other more qualitative assessments that include non-market and cultural values; and
- Integrate the understanding of human behavior, engineering, and genomics to expand the range of choice in responding to climate change by providing and thoroughly evaluating new options for adaption and mitigation that improve economic development, energy, health, and food security.

2. Ensure availability of observations, monitoring, and infrastructure for critical data collection and analysis

Our understanding and ability to assess changes in climate and other global processes is based on a comprehensive and sustained system of observations that document the history of climate, socioeconomic, and related changes at spatial and time scales relevant to global, regional, and sectoral needs. The most recent USGCRP Strategic Plan[5] states that to advance scientific knowledge of an integrated natural and human Earth system, an interoperable and integrated observational, monitoring, and data access capability is also essential. This observational capability is needed to gain the fundamental scientific understanding of essential status, trends, variability, and changes in the Earth system. It should include the physical, chemical, biological, and human components of the Earth system over multiple space and time scales.

To attain their full value, observational systems must provide data that are responsive to the needs of decision-makers in government, industry, and society. These needs include observations and data that can inform the nation's strategies to respond to climate and global change, including, for example, efforts to limit emissions, monitor public health, capture and store carbon, monitor changes in ocean processes, and implement adaptation strategies. This will require establishing explicit baseline conditions, specifying spatial detail and temporal frequency of observations, including social data, and setting standards for metadata (information about collected data), interoperability, and regulatory and voluntary reporting, such as those outlined in the *Informing an Effective Response to Climate Change Panel Report* of the National Research Council's *Americas Climate Choices* series.[8] These data need to be openly and widely available in order to support the best and most comprehensive science and for use in decision-making by a range of stakeholders.

This assessment shows that enhanced research and development will be necessary to ensure that the scope and integration of relevant scientific data improves overall utility for decision-makers, including better ways to communicate metadata, data quality, and uncertainties. The observations must include critical geophysical variables such as temperature, precipitation, sea level changes, ocean circulation, atmospheric composition, and hydrology; the essential parameters that describe the biosphere; and social science information on drivers, impacts, and responses to climate and other global changes. More comprehensive and integrated data capabilities are needed to document the processes and patterns that drive natural and social feedbacks and better describe the mechanisms of abrupt change. Progress is needed in particular for data-poor regions, focusing on inadequately documented socioeconomic, ecological, and health-related factors, and under-observed regional and sectoral data. There are opportunities to take advantage of citizen science observations where appropriate; monitor system resilience and robustness; and attend to physical and social systems that are not currently observed with sufficient temporal or spatial resolution to enable vulnerability analysis and decision support at regional and sectoral scales. More explicitly, strategic integration of our nation's observations, monitoring, and data capabilities should be considered in order to:

- **Sustain and integrate the nation's capacity to observe** long-term changes in the Earth system and improve fundamental understanding of the complex causes and consequences of global change, including integration of essential socioeconomic, health, and ecological observations;

- **Maintain and enhance advanced modeling capability**, including high-performance computing infrastructure, improvements in analysis of large and complex data sets, comprehensive Earth system and integrated assessment models, reanalysis, verification, and model comparisons;

- **Better integrate observations and modeling** to advance scientific understanding about past, present, and future climate within government, industry, and civil society; and

- **Develop more fully the components and structure of a national climate and global change indicator system** to support assessment that includes indicators of climate change, impacts, vulnerabilities, opportunities, and preparedness as well as trends and changes in land use, air and water pollution, water supply and demand, extreme events, diseases, public health, and agronomic data, coastal and ocean conditions (such as marine ecosystem health, ocean acidity, sea level, and salinity), cryosphere data (such as snow, sea ice conditions, ice sheets and glacier melt rates), and changes in public attitudes and understanding of climate change. All of these are important to assessing climate change, and should eventually be better coordinated at local, as well as national and regional levels in collaboration with local agencies.

3. Build capacity for climate assessment through training, education, and workforce development

Building human capacity for improved assessments requires expansion of skills within the existing public and private sectors and developing a much larger workforce that excels at critical and interdisciplinary thinking. Useful capacities include the ability to facilitate and communicate research and practice, manage collaborative processes to allow for imaginative analysis and solutions, develop sustainable technologies to reduce climate risks, and build tools for decision-making in an internationally interdependent world.

A deeper understanding of the processes and impacts of climate change, disaster risk reduction, energy policy impacts, ecosystem services and biodiversity, poverty reduction, food security, and sustainable consumption requires new approaches to training and curriculum, as well as research to evaluate the effectiveness of different approaches to research and teaching.

Assessments will benefit from activities that:

- **Strengthen approaches to education about climate, impacts, and responses** including developing and evaluating the best ways to educate in the fields of science (natural and social), technology, engineering, and mathematics and related fields of study (such as business, law, medicine, and other relevant professional disciplines). Ideally, such training would include a deeper understanding of the climate system, natural resources, adaptation and energy policy options, and economic sustainability, and would build capacity at colleges and institutions, including minority institutions such as tribal colleges; and

- **Identify increasingly effective approaches to developing a more climate-informed society** that understands and can participate in assessments, including alternative media and methods for communication; this could also include a program to certify climate interpreters to actively assist decision-makers and policymakers to understand and use climate scenarios.[8]

4. Enhance the development and use of scenarios

Scenarios are "coherent, internally consistent and plausible descriptions of possible future states of the world"[9] that provide reasoned projections of energy and land use, future population levels, economic activity, the structure of governance, social values, and patterns of technological change. They survey, integrate, and synthesize science, within and among scientific disciplines and across sectors and regions. Such scenarios are essential tools that enable projections of emissions, climate, vulnerabilities, and global change. They are indispensable for linking science and decision-making and for assessing choices about America's climate future.

Stakeholders and scientists within this assessment identified a need for more fully developed scenario-building capabilities that better enable assessments at regional and sectoral scales in timeframes of relevance to policy and decision-making and that more effectively reflect climate and global change at these scales.

Achieving capacity in scenario development will:

- **Enhance understanding of how and why climate may change and its implications,** especially at the regional scale. For example, a set of scenarios can be used to better understand the way energy, land use, and policy choices create alternative emissions pathways; how changes at global scales can be downscaled to estimate local climate possibilities; how various socioeconomic development pathways increase or decrease climate vulnerability; and to assess alternative strategies for reducing emissions and implementing adaptation; and

- **Develop new methods, tools, and skills for applying scenarios to policy development** at local levels in order to broaden society's understanding of a changing climate and to analyze the full range of policy choices. In addition, improve capabilities in integrated assessment modeling to inform policy analysis and allow stakeholders to co-produce information and explore options for local and national decisions.

5. Promote international research and collaboration

Research efforts in support of climate assessment are very dependent on the international research community. International teams conduct Earth system monitoring and analysis using observing systems that cannot be funded and maintained by any one country alone. Many of the impacts of climate change in the U.S. are closely linked to how climate affects other parts of the world. There is general understanding that impacts of climate change on U.S. socioeconomic systems are mediated or amplified through globally connected commodity chains and prices; more detailed research on climate change and its impacts elsewhere is needed to provide accurate assessments of what could happen to U.S. regional and local economies. The U.S. has the capacity to leverage investments in collaborative international climate and global change scientific research efforts, examples of which include IGBP (International Geosphere-Biosphere Programme), WCRP (World Climate Research Programme), DIVERSITAS (an international program of biodiversity science), IHDP (International Human Dimensions Programme) (as they evolve into or in affiliation with the new Future Earth program), and IGFA (International Group of Funding Agencies for Global Change Research).

Supporting international collaborative research will:

- **Contribute to international systems of data collection, monitoring, indicators, and modeling** that closely track and project changes in Earth system dynamics, climate, human drivers, and climate impacts that are needed for national and international assessments;

- **Assess the implications of climate change for globally shared common resources** such as the oceans, polar regions, and migratory species; and

- **Fill important gaps in understanding of how climate change in other countries** affects U.S. food, energy, health, manufacturing, and national security.

Conclusions

This chapter summarizes research recommendations across a broad range of topics – research that the assessment authors deem essential to support future assessments. The authors recognize that federal agencies and others are making progress on many of these research areas and that sustained assessment is included in the goals of the USGCRP.

While the research goals discussed in this chapter are not ranked, the objectives listed below can be used as criteria for prioritizing these activities. The nation's federal research investments in support of the sustained assessment strategy should be designed to enhance the nation's ability to limit climate-related risk and increase the utility of scientific understanding in supporting decisions.

- **Promote understanding of the fundamental behavior of the Earth's climate and environmental systems:** The consequences of climate variability and change will require enhanced investment in use-inspired research using both fundamental and applied analysis, providing a foundation for the nation's sustained assessment process;

- **Promote understanding of the socioeconomic impacts of a changing climate:** Provide comprehensive understanding, including the development of indicators of the impacts and consequences of climate variability and change for regions and sectors within the United States;

- **Build capacity to assess risks and consequences:** Support improved, timely, and accessible estimations and projections of climate and other global change risks, their consequences and relevance for stakeholders, associated costs and benefits, and interactions with other stresses;

- **Support research that enables infrastructure for analysis:** Sustain and enhance critical infrastructure, including observations and data essential to monitoring trends, projecting climate risks, and evaluating the effectiveness of responses in decision-making and policy implementation;

- **Build decision-support capacity:** Build the knowledge base essential for decision support including developing and evaluating climate mitigation and adaptation solutions, technology innovation, institutions, and behavioral change; and

- **Support engagement of the private sector and investment communities:** Develop strategies to leverage federal research investments by engaging the private sector more fully in research and technology development, including partnerships with the nation's universities and scientific research institutions, to address critical gaps in knowledge and to build the nation's future scientific, technical, and sustained assessment capacities.

- **Leverage private sector, university, and international resources and partnerships:** Take advantage of topics and expertise where the U.S. can leverage and complement private sector and university capabilities, obtain return on research investments, and lead internationally on research investment efforts; build capacity through education and training; support humanitarian response; and fill critical gaps in global knowledge of relevance to the United States.

29: RESEARCH NEEDS FOR CLIMATE AND GLOBAL CHANGE ASSESSMENTS

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29: RESEARCH NEEDS FOR CLIMATE AND GLOBAL CHANGE ASSESSMENTS

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Chapter Process:

The author team asked each of the other chapter author teams to identify important gaps in knowledge and key research needs in the course of writing their chapters, particularly in the context of the needs for research to support future assessments. In addition to the lists provided by each chapter author team, the team also drew on analyses from over 100 technical and public review suggestions and a wide variety of technical and scholarly literature, especially the U.S. Global Change Research Program's Strategic Plan[5] and the National Research Council's *America's Climate Choices* reports,[2,3,4,8,10] to compile a list of potential research needs. Using expert deliberation, including a number of teleconference meetings and email conversations among author team members, the author team agreed on high-priority research needs, organized under five research goals.

Climate Change Impacts in the United States

CHAPTER 30

SUSTAINED ASSESSMENT: A NEW VISION FOR FUTURE U.S. ASSESSMENTS

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On the Web: http://nca2014.globalchange.gov/report/response-strategies/sustained-assessment

30 SUSTAINED ASSESSMENT: A NEW VISION FOR FUTURE U.S. ASSESSMENTS

A primary goal of the U.S. National Climate Assessment (NCA) is to help the nation anticipate, mitigate, and adapt to impacts from global climate change, including changes in climate variability, in the context of other national and global change factors. Since 1990, when Congress authorized the U.S. Global Change Research Program (USGCRP) through the Global Change Research Act[1] and required periodic updates on climate science and its implications, researchers from many fields have observed significant climate change impacts in every region of the United States. The accelerating pace of these changes (for example, the recent rapid reductions observed in the extent and thickness of Arctic sea ice), as well as scenario-based projections for future climate changes and effects, is articulated in this third NCA.

Based on recommendations stemming from the National Research Council (NRC), USGCRP in its most recent strategic plan[2] identified the rationale and benefits of implementing a sustained assessment process. In response, a vision for a new approach to assessments took shape as the third NCA report was being prepared. The vision includes an ongoing process of working to understand and evaluate the nation's vulnerabilities to climate variability and change and its capacity to respond. A sustained assessment, in addition to producing quadrennial assessment reports as required by law, recognizes that the ability to understand, predict, assess, and respond to rapid changes in the global environment requires ongoing efforts to integrate new knowledge and experience. It accomplishes this by: 1) advancing the science needed to improve the assessment process and its outcomes, building associated foundational knowledge, and collecting relevant data; 2) developing targeted scientific reports and other products that respond directly to the needs of federal agencies, state and local governments, tribes, other decision-makers, and end users; 3) creating a framework for continued interactions between the assessment partners and stakeholders and the scientific community; and 4) supporting the capacity of those engaged in assessment activities to maintain such interactions.

To provide decision-makers with more timely, concise, and useful information, a sustained assessment process would include both ongoing, extensive engagement with public and private partners and targeted, scientifically rigorous reports that address concerns in a timely fashion. A growing body of assessment literature has guided and informed the development of this approach to a sustained assessment.[3,4,5]

The envisioned sustained assessment process includes continuing and expanding engagement with scientists and other professionals from government, academia, business, and non-governmental organizations. These partnerships broaden the knowledge base from which conclusions can be drawn. In addition, sustained engagement with decision-makers and end users helps scientists understand what information society wants and needs, and it provides mechanisms for researchers to receive ongoing feedback on the utility of the tools and data they provide.

An ongoing process that supports these forms of outreach and engagement allows for more comprehensive and insightful evaluation of climate changes across the nation, including how decision-makers and end users are responding to these changes. The most thoughtful and robust responses to climate change can be made only when these complex issues, including the underlying science and its many implications for the nation, are documented and communicated in a way that both scientists and non-scientists can understand.

This sustained assessment process will lead to better outcomes for the people of the United States by providing more relevant, comprehensible, and usable knowledge to guide decisions related to climate change at local, regional, and national scales. Additional details about the components of the sustained assessment process are provided in "Preparing the Nation for Change: Building a Sustained National Climate Assessment Process," the first special report of the National Climate Assessment and Development Advisory Committee.[6]

Contributions of a Sustained Assessment Process

A sustained assessment process will not only include producing the quadrennial assessment reports required by the 1990 GCRA, but it also will enable many other important outcomes. A well-designed and executed sustained assessment process will:

1. Increase the nation's capacity to measure and evaluate the impacts of and responses to further climate change in the United States, locally, regionally, and nationally.
2. Improve the collection of assessment-related critical data, access to those data, and the capacity of users to work with datasets – including their use in decision support tools – relevant to their specific issues and interests. This includes periodically assessing how users are applying such data.

3. Support the creation of the first integrated suite of national indicators of climate-related trends across a variety of important climate drivers and responses.

4. Catalyze the production of targeted, in-depth special assessment reports on sectoral topics (for example, agriculture), cross-sectoral topics (for example, the connection between water and energy production), regional topics, and other topics that will help inform Americans' climate choices about mitigation and adaptation. These reports will generate new insights about climate change, its impacts, and the effectiveness of societal responses. In addition, a second report category, referred to as foundational reports, will focus on improvements to specific aspects of the process (for example, scenarios and indicators) to reinforce the foundation for the overarching, but necessarily more constrained, quadrennial assessment reports.

5. Facilitate the creation of, support, and leverage a network of scientific, decision-maker, and user communities for extended dialog and engagement regarding climate change.

6. Provide a systematic way to identify gaps in knowledge and uncertainties faced by the scientific community and by U.S. domestic and international partners and to assist in setting priorities for their resolution.

7. Enhance integration with other assessment efforts such as the Intergovernmental Panel on Climate Change and modeling efforts such as the Coupled Model Intercomparison Project.

8. Develop and apply tools to evaluate progress and guide improvements in processes and products over time. This will support an iterative approach to managing risks and opportunities associated with changing global and national conditions.

Assessments facilitate the collection of different kinds of information that can be integrated to yield new and useful scientific insights. The vision for the sustained assessment process is to continue to build knowledge about human and natural systems and their interactions to better understand the risks and opportunities of global change at multiple spatial and temporal scales. The sustained assessment process also can help define the range of information needs of decision-makers and end users relative to adaptation and mitigation, as well as the associated costs of impacts and benefits of response actions. Moreover, it is by its very nature a continuous process, uniquely positioned to support an iterative, risk-based approach to adaptation.

Finally, although a sustained assessment process allows for ongoing improvements in products and processes, it also requires underlying support systems. These can include access to observational data sources, support networks, and information management systems such as the Global Change Information System (GCIS; see section on "Data Collection, Access, and Analysis"). Other fundamental support for assessments includes various types of integrated and vulnerability assessment models, climate model intercomparison projects, data streams (for example, emissions data and socioeconomic data), processes for building scenarios and deploying them at critical junctures in the assessment process, and evaluation approaches.

Assessment Capacity

Scientific assessments require substantial scientific expertise and judgment, involving skills atypical of those required for routine research.[4,5] Assessment capacity includes engaging knowledgeable and experienced people, developing networks to promote interactions, identifying and mentoring new scientific talent, and building in-depth understanding of a variety of economic, technical, and scientific topics. Building and maintaining capacity through all of these approaches is therefore critical to the smooth and efficient functioning of the assessment process.

Sustained interactions among scientists and stakeholders have consistently been shown to improve the utility and effectiveness of assessment processes and outcomes[5] and to facilitate the development of decision support tools.[7] A sustained assessment provides the necessary coordination and infrastructure needed to maintain an ongoing dialog among producers and users of information so that decision-makers can manage risks and take advantage of opportunities more efficiently. This provides the capacity and flexibility to react to, and take advantage of, rapidly advancing developments in decision and climate science and changing conditions to inform robust decision-making and improve the utility and timeliness of future quadrennial assessment reports.

Data Collection, Access, and Analysis

Credible scientific information is needed on an ongoing basis to support fundamental understanding of the climate system and its interactions with ecological, economic, and social systems – and for the development of adaptation and mitigation strategies. Improved systems for data access can more effectively meet the requests of stakeholders for accessible, relevant, and timely information. An ongoing process can build a more complete information base relevant to climate change related impacts and vulnerabilities, and it can result in more sophisticated scientific analyses that support the mandated quadrennial assessment reports in a more efficient and effective manner. Selecting which data to collect and analyze is a critical component of assessments of change. In addition, for certain assessment-related purposes, use of traditional knowledge may be appropriate and require different analytical approaches.

The sustained assessment process will facilitate the development and maintenance of a web-based assessment information discovery, access, and retrieval system that facilitates easy access to a range of information for those who need it, in a timely and authoritative manner (the GCIS of the USGCRP). A major short-term goal is to provide transparent and highly-linked access to the data used to support conclusions in the third NCA report, but this is only the first step in a much larger effort. Initially targeted audiences include assessment practitioners across various sectors and governmental levels.

Indicators

Indicators are measurements or calculations that represent important features of the status, trends, or performance of a system (such as the economy, agriculture, natural ecosystems, or Arctic sea ice cover). Indicators are used to identify and communicate changing conditions to inform both research and management decisions.[8] The NCA indicator system is intended to focus on key aspects of change – as well as vulnerabilities, impacts, and states of preparedness – to inform decision-makers and the public. In the context of ongoing assessment activities, these indicators can be tracked to provide timely, authoritative, and climate-relevant measurements regarding the status, rates of change, and trends of key physical, ecological, and societal variables.

Special and Foundational Reports

As currently envisioned, the sustained assessment process also paves the way for additional types of assessment-related reports that can help inform local, regional, and sectoral mitigation and adaptation activities and provide a foundation for more useful and more comprehensive quadrennial assessment reports. Completing in-depth assessments of national or regional importance and providing a constantly improving foundation for the quadrennial assessment reports provides for significant flexibility and enhanced policy relevance. Special topical assessment reports can investigate emerging issues of concern or help decision-makers understand the tradeoffs among different courses of action. Moreover, these types of assessments can encompass a more holistic, multi-disciplinary, and integrated approach that considers various types of data analyses that may not have been previously attempted. These more focused reports that emerge from ongoing assessment activities can blend the objectives of incorporating the latest science with responding relatively quickly to the most pressing stakeholder and government needs. Finally, foundational reports also can be produced on scenarios of climate change, sea level rise, demography, land-use change, and other issues critical to the assessment process.

A Network to Foster Partnerships, Encourage Engagement, and Develop Solutions

The USGCRP has long recognized the importance of partnerships, effective two-way communication, and ongoing and meaningful engagement.[2] The five NRC *America's Climate Choices* reports published in 2010 and 2011 also underscore the essential nature of this engagement (for example, NRC 2010[9]). Partnerships and engagement strategies among federal and non-federal participants are needed to: 1) communicate effectively about the assessment, including its products and processes and their relevance as actionable information;[10] 2) encourage participation and knowledge sharing; 3) create opportunities for meaningful engagement of end users and public and private decision-makers to inform the substance of the assessment; and 4) offer opportunities for input, direction, review, and feedback.

An important component of the new sustained assessment vision is NCAnet: a "network of networks" that helps to foster engagement in the NCA process and communicate products to a broader audience (for additional details about NCAnet, please see Appendix 1: Process). This network of partner organizations, including private sector, government, non-governmental organizations, and professional societies, leverages resources and facilitates communication and partnerships. By its first meeting in January 2012, NCAnet consisted of over three dozen partner organizations. Much of the network's subsequent growth to over 100 partner organizations (as of fall 2013) has been driven by the partners' own outreach and interest in building a community around the practice of assessment. NCAnet can assist in developing and supporting diverse science capabilities and assessment competencies within and outside of the Federal Government.

Evaluation of the Process

Ongoing evaluation of assessment processes and products, as well as incorporating the lessons learned over time, is a specific objective of the USGCRP Strategic Plan.[2] Evaluation efforts are considered integral to enabling learning and adaptive management of the assessment process, measuring the ability to meet both legally required objectives and strategic goals, maintaining institutional memory, and improving the assessment process and its contributions to scientific understanding as well as to society. Ongoing improvements in the assessment process also will support an iterative approach to decision-making in the context of rapid change.

Recommendations on Research Priorities

The GCRA requires regular evaluations of gaps in knowledge and assessments of uncertainties that require additional scientific input. A sustained assessment process provides for regular updates on science needs to the USGCRP's annual research prioritization process, as well as to the triennial and decadal revisions to its research plan.

30: SUSTAINED ASSESSMENT: A NEW VISION FOR FUTURE U.S. ASSESSMENTS

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30: SUSTAINED ASSESSMENT: A NEW VISION FOR FUTURE U.S. ASSESSMENTS

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

Planning for the sustained assessment process, and for including a description of the process in a chapter of the third NCA report, began as soon as the report process was launched. Mechanisms for creating and implementing a sustained process were included as key discussion points in early NCA process workshops.[11] Prior to the formation of the chapter author teams, the need for a sustained assessment was described in the NCA Strategy Summary.[12] The amended charter for the National Climate Assessment and Development Advisory Committee (NCADAC) specifies that the NCADAC is "to provide advice and recommendations toward the development of an ongoing, sustainable national assessment of global change impacts and adaptation and mitigation strategies for the Nation."[13] To that end, the NCADAC formed a working group on sustained assessment, and the USGCRP Interagency National Climate Assessment Working Group (INCA) made this topic a priority in their regular meetings. The USGCRP also established "conduct sustained assessments" as one of four programmatic pillars in its recent Strategic Plan.[2]

The sustained assessment author team drew on a wide variety of source materials in framing the need for a sustained assessment process, including calls for sustained assessment in both previous National Climate Assessment reports[14] and in several publications from the National Research Council[5,9,15] that focused specifically on the National Climate Assessment. The author team also considered a rich literature on assessments in general (for example, Farrell and Jäger 2005 and Mitchell et al. 2006[4]). In developing the chapter describing the sustained assessment process, the author team first worked with the NCADAC, especially the initial NCADAC working group on sustained assessment, and the INCA to develop a vision for sustained assessment and a list of activities required to implement this vision. They then collected feedback from each of the chapters' convening lead authors, agencies, chairs of other NCADAC working groups, and targeted stakeholders. Drawing on these comments and the knowledge bases cited above, the author team came to consensus on the objectives and categories of activities provided in the chapter through teleconference and email discussions. The NCADAC formed a new author team to produce a longer special report on the sustained assessment process. The report was completed in the late summer of 2013.[6]

APPENDIX 1 REPORT DEVELOPMENT PROCESS

The National Climate Assessment (NCA) supports the U.S. Global Change Research Program (USGCRP) and its Strategic Plan[1] in multiple ways. The Strategic Plan focuses on climate science that informs societal objectives; the USGCRP program and the NCA help build an information base to support climate-related decisions, including decisions to reduce human contributions to future climate change, and to adapt to changes that are occurring now and are projected in the future. In order to facilitate the integration of federal science investments with academic, public, and private sector climate change research, the Third NCA process focused on building strong relationships with stakeholders and experts outside the government. Early in the process, the National Climate Assessment and Development Advisory Committee (NCADAC) and NCA Coordination Office developed a strategy to engage a broad range of the American public. Open participation, communication, and feedback have been integral to the preparation of this far-reaching assessment.[2]

NCA Goal and Vision

As established by the NCADAC,[3] the overarching goal of the NCA process is to enhance the ability of the United States to anticipate, mitigate, and adapt to changes in the global environment that are increasingly linked to human activities.

The vision is to advance an inclusive, broad-based, and sustained process for developing, assessing, and communicating scientific knowledge of the impacts, risks, vulnerabilities, and response options associated with a changing global climate, and to support informed decision-making across the United States.

Legislative Foundations

The NCA is conducted under the auspices of the Global Change Research Act (GCRA) of 1990.[4] The mandate for the U.S. Global Change Research Program as a whole is: “To provide for development and coordination of a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change.”

Section 106 of the GCRA requires a report to the President and the Congress every four years that integrates, evaluates, and interprets the findings of the USGCRP; analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

Institutional Foundations

U.S. Global Change Research Program

USGCRP is a federation of the research components of 13 federal departments and agencies that supports the largest investment in climate and global change research in the world. USGCRP coordinates research activities across agencies and establishes joint funding priorities for research. USGCRP’s Strategic Plan, adopted in 2012, focuses on four major goals: advance science, inform decisions, conduct sustained assessments, and communicate and educate.[1] The USGCRP agencies maintain and develop observations, monitoring, data management, analysis, and modeling capabilities that support the nation’s response to global change. The agencies that comprise the USGCRP are:

U.S. Department of Agriculture
U.S. Department of Commerce
U.S. Department of Defense
U.S. Department of Energy
U.S. Department of Health & Human Services
U.S. Department of the Interior
U.S. Department of State
U.S. Department of Transportation
U.S. Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation
The Smithsonian Institution
U.S. Agency for International Development

The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities. SGCR operates under the direction of the National Science and Technology Council's (NSTC) Committee on Environment, Natural Resources, and Sustainability (CENRS) and is overseen by the White House Office of Science and Technology Policy (OSTP). The SGCR coordinates interagency activities through the USGCRP National Coordination Office (NCO) and interagency working groups (IWGs).

National Climate Assessment (NCA) Components

The **Interagency NCA Working Group (INCA)** is comprised of representatives of the 13 government agencies listed above, plus additional agencies that have chosen to engage in supporting the NCA activities. INCA is responsible for coordinating, developing, and implementing interagency activities for the NCA, providing critical input to identify and support future NCA products, and developing interagency assessment capacity at the national and regional scales. Through INCA, the agencies have supported the development of the 30 chapters and the process to create the Third NCA report in a variety of ways.

The **National Climate Assessment and Development Advisory Committee (NCADAC)** is a 60-member federal advisory committee established by the Department of Commerce on behalf of USGCRP. Forty-four non-federal NCADAC members represent the public, private, and academic sectors; 16 non-voting ex-officio members represent the USGCRP agencies, the Department of Homeland Security, the SGCR, and the White House Council on Environmental Quality. The NCADAC charter charges the group with developing the Third NCA report and with providing recommendations about how to sustain an ongoing assessment process. The NCADAC selected the authors of the individual chapters and coordinated many of the assessment activities leading to this report. This included NCADAC meetings and more than 20 NCADAC subcommittee working groups on specific assessment needs (for example, regional and sectoral integration, engagement and communication, indicators, and international linkages). An Executive Secretariat of 12 individuals (a subset of the full committee) helps to coordinate the activities of the full committee.

The **NCA Coordination Office** is a part of the USGCRP National Coordination Office in Washington, D.C. The office is supported and funded through an interagency agreement with the University Corporation for Atmospheric Research (UCAR). A team of UCAR staff and federal detailees (agency employees as-

Organization of NCA components

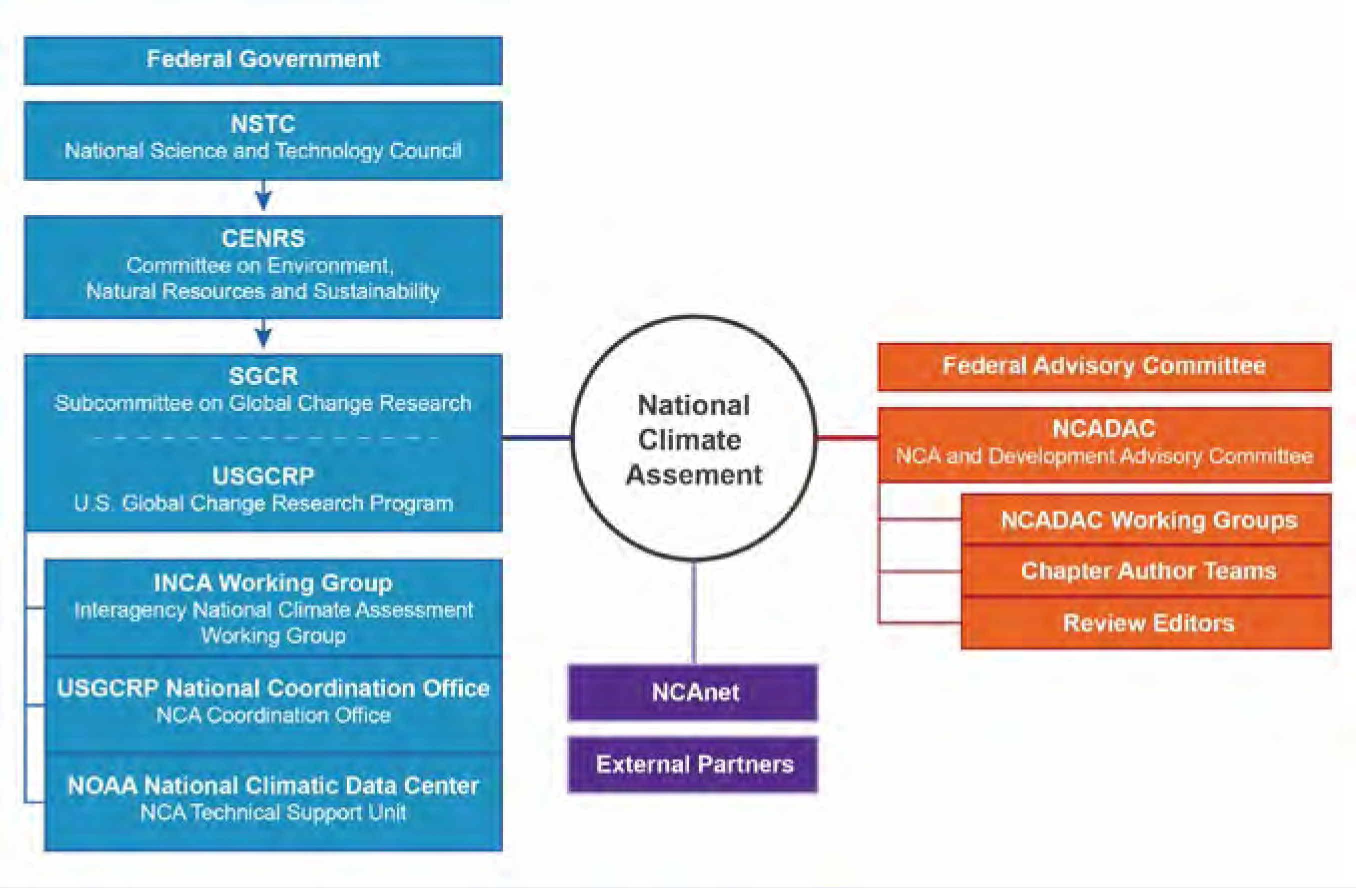

Figure 1.

signed to the NCA Coordination Office) with expertise in planning, writing, and coordinating collaborative climate and environmental science and policy activities provides support for the development of the NCA report and sustained assessment.

The **NCA Technical Support Unit (TSU)** is funded by the National Oceanic and Atmospheric Administration (NOAA) and is located at NOAA's National Climatic Data Center in Asheville, NC. The TSU staff provides multiple kinds of support to the NCA, including climate science research, data management, web design, graphic design, technical and scientific writing and editing, publication production, and meeting support.

The **National Climate Assessment Network (NCAnet)** consists of more than 100 partner organizations that work with the NCA Coordination Office, NCADAC, report authors, and USGCRP agencies to engage producers and users of assessment information.[5] Partners extend the NCA process and products to a broad audience through the development of assessment-related capacities and products, such as collecting and synthesizing data or other technical and scientific inputs into the NCA, disseminating NCA report findings to a wide range of users, engaging producers and users of assessment information, supporting NCA events, and producing communications materials related to the NCA and its report findings.

Creating the Third NCA Report

Process Development

The NCA Engagement Strategy provides a vision for participation, outreach, communication, and education processes that help make the NCA process and products accessible and useful to a wide variety of audiences. The overall goal of engagement is to create a more effective and successful NCA – improving the processes and products of the effort so that they are credible, salient, and legitimate and building the capacity of participants to engage in the creation and use of NCA products in decision-making.[2] The strategy describes a number of mechanisms through which scientific and technical experts, decision-makers, and members of the general public might learn about and participate in the NCA process.

As part of the assessment process, a series of 14 process workshops helped establish consistent assumptions and methodologies. The resulting reports provide a consistent foundation for the technical input teams and chapter authors.

The NCA Coordination Office organized listening sessions, symposia, and sessions at professional society meetings during the development of the NCA report and sustained assessment process. These sessions provided updates on the NCA process, solicited broad input from subject matter experts, and collected feedback on the approach, topics, and methodologies under consideration.

Third National Climate Assessment Report Process

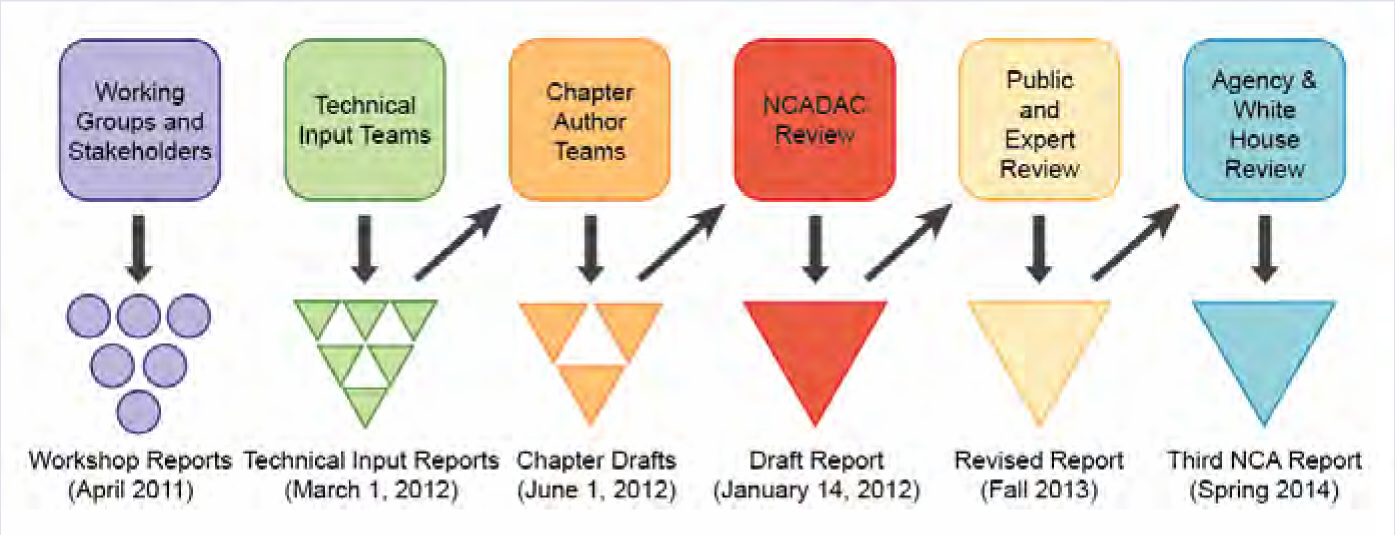

Figure 2. This graphic illustrates the activities and products that were developed during the Third NCA report development process.

Technical Input Reports

A public Request for Information[6] resulted in submission of more than 500 technical input documents authored by more than 800 individuals from academia, industry, and government, including 25 technical inputs[7] sponsored by USGCRP agencies. These inputs included documents and data sets for review and consideration by the author teams that developed the NCA report. Technical input authors used a variety of mechanisms to engage stakeholders in the scoping, writing, and review of their documents, including workshops, web-based seminars, and public comment periods, among other methods.

In addition, the Technical Support Unit climate science team developed nine peer-reviewed regional climate scenario documents (one for each of the eight regions and one for the contiguous United States),[8] providing a scientific consensus view of historical climate trends and projections under the IPCC Special Report on Emissions Scenarios (SRES) A2 and B1 scenarios.[9] A separate interagency committee developed four peer-reviewed sea level rise scenarios.[10] These scenarios were used by chapter authors as underpinnings for their impact assessments.

Third NCA Report Draft Development and Review

The NCADAC selected two to three convening lead authors and approximately six lead authors for each chapter, based on criteria that included expertise, experience, geography, and ensuring a variety of perspectives. They included authors from the public and private sectors, non-governmental organizations, and universities. Beginning in December 2011, each of the author teams met multiple times by phone, web, and in person to produce and refine drafts of their chapters. Traceable accounts developed for each chapter provide transparent information about the authors' decision processes, scientific certainty, and their level of confidence related to the key findings of their respective chapters. All authors served in a volunteer capacity.

After reviewing the draft Third NCA report, the NCADAC released it for public review and comment on January 14, 2013.[11] Concurrently, the NCA underwent an independent expert review by the National Research Council, a part of the National Academies. A three-month review period allowed individuals and groups to examine the draft and provide comments aimed at improvement. The comments were provided using a secure online comment system to ensure that all comments were captured and appropriately addressed.

Regional town hall meetings, conducted by the NCA Coordination Office (one per region, plus coasts) and by NCAnet partners (three additional meetings), brought together authors, NCADAC members, and members of the public to discuss the NCA process and encourage participants to submit comments on the draft report. Report authors, NCADAC members, NCA staff, and NCAnet partners organized, spoke at, and participated in sessions at professional society meetings, web-based seminars, community meetings, and other events similarly aimed at providing an overview of the draft report and encouraging comments.[12]

By the time the public comment period closed on April 12, 2013, the online comment system received 4,161 comments from 644 government, non-profit, and commercial sector employees, educators, students, and the general public. Chapter author teams and the NCADAC amended the draft report in response to comments and prepared written responses to each comment received, and external review editors evaluated the adequacy of the responses to the comments on each chapter. As the result of a NCADAC consensus decision, the entire review process was "blind", that is, NCADAC members and authors did not know the identity of commenters when responding to each comment. The public comments (including commenters' identities) and the chapter authors' responses to those comments were posted online with the final report.

The National Research Council provided a second review of the report, and the NCADAC considered this review in developing a final draft for submission to federal agencies for review in fall 2013.

NCA Final Report

Any adjustments to the NCADAC's Fall 2013 draft as a result of the government review process were made with the authors' approval, and the NCADAC approved the final form of the report in Spring 2014. Having been accepted and finalized following government review, the report is now provided as the assessment by the Federal Government of the United States, pursuant to the requirements of the Global Change Research Act. A number of products derived from the report support the outreach activities following the report release.

Engagement Activities

What follows is a sample of activities convened in support of the development of the Third NCA Report. A full list of activities is available online at http://assessment.globalchange.gov.

NCADAC Meetings: All meetings were open the public. The presentations, documents, and minutes for each NCADAC meeting are available online at http://www.nesdis.noaa.gov/NCADAC/Meetings.html.

- April 4-6, 2011, Washington, DC http://www.nesdis.noaa.gov/NCADAC/April_4_Meeting.html
- May 20, 2011, Teleconference
- August 16-18, 2011, Arlington, VA

- November 16-17, 2011, Boulder, CO
- April 10, 2012, Teleconference
- June 14-15, 2012, Washington, DC
- August 15, 2012, Teleconference
- September 27, 2012, Teleconference
- November 14-15, 2012, Silver Spring, MD
- January 11, 2013, Teleconference
- May 13, 2013, Teleconference
- July 9-10, 2013, Washington, DC
- November 18, 2013, Teleconference
- February 20-21, 2014, Washington, DC
- Spring 2014, Final approval of the Third NCA via teleconference

Process and Methodology Workshops: Reports from these workshops are available online at http://www.globalchange.gov/what-we-do/assessment/nca-activities/workshop-and-meeting-reports.

- Midwest Regional Workshop, February 2010, Chicago, IL
- Strategic Planning Workshop, February 2010, Chicago, IL
- Scoping the Product(s) and Work Plan for the Third National Assessment, June 2010, Washington, DC [no report available]
- Communications Scoping Meeting, July 2010, Washington, DC [no report available]
- International Scoping Meeting, August 2010, Washington, DC [no report available]
- Knowledge Management Workshop, September 2010, Reston, VA
- Regional Sectoral Workshop, November 2010, Reston, VA
- Ecological Indicators Workshop, November 2010, Washington, DC
- Scenarios Workshop, December 2010, Arlington, VA
- Climate Change Modeling and Downscaling Workshop, December, 2010, Arlington, VA
- Valuation Techniques and Metrics Workshop, January 2011, Arlington, VA
- Vulnerability Assessments Workshop, January 2011, Atlanta, GA
- Physical Climate Indicators Workshop, March 2011, Washington, DC
- Societal Indicators Workshop, April 2011, Washington, DC

Agency-Sponsored Technical Input Development Workshops

- Monitoring Changes in Extreme Storm Statistics: State of Knowledge, July 2011, Asheville, NC
- Forestry Sector Stakeholder Workshop, July 2011, Atlanta, GA
- Land Use and Land Cover Stakeholder Workshop, November 1011, Salt Lake City, UT
- Energy Supply and Use Workshop, November 2011, Washington, DC
- Energy, Water, Land Planning Meeting, November 2011, Washington, DC
- Urban Infrastructure and Vulnerabilities Workshop, November 2011, Washington, DC
- Trends and Causes of Observed Changes in Heat Waves, Cold Waves, Floods, and Drought, Nov. 2011, Asheville, NC
- Trends in Extreme Winds, Waves, and Extratropical Storms along the Coasts, January 2012, Asheville, NC
- Ecosystems, Biodiversity, and Ecosystem Services Workshop, January 2012, Palo Alto, CA
- Water Sector Technical Input Workshop, January 2012, Washington, DC
- Coastal Zone Stakeholders Meeting, January 2012, Charleston, SC
- Climate Change and Health Workshop - Southeast, February 2012, Charleston, SC
- Rural Communities Workshop, Feb. 2012, Charleston SC
- Climate Change and Health Workshop - Northwest, February 2012, Seattle, WA

Listening Sessions

- Annual Meeting of the Association of American Geographers, April 2011, Seattle, WA
- American Water Resource Association Spring Specialty Conference, April 2011, Baltimore, MD
- International Symposium on Society and Resource Management, June 2011, Madison, WI
- Annual Soil and Water Conservation Society Conference, July 2011, Washington, DC
- Ecological Society of America Annual Meeting, August 2011, Austin, TX
- American Meteorological Society Annual Meeting, January 2012, New Orleans, LA

Regional Town Hall Meetings

- Hawai'i & Pacific Islands Town Hall, December 2012, Honolulu, HI
- Southwest Regional Town Hall, January 2013, San Diego, CA
- Northeast Regional Town Hall, January 2013, Syracuse, NY
- Great Plains Regional Town Hall, February 2013, Lincoln, NE
- Alaska Regional Town Hall, February 2013, Anchorage, AK
- Midwest Regional Town Hall, February 2013, Ann Arbor, MI
- Southeast Regional Town Hall, February 2013, Tampa, FL
- Northwest Regional Town Hall, March 2013, Portland, OR
- Oceans and Coasts Town Hall, April 2013, Washington, DC

NCAnet Partners Activities

The NCAnet Partners meet monthly (since January 2012) in Washington, DC; teleconference and web conference capabilities allow participants to join remotely. NCAnet Partners hosted more than 25 events around the country for the public and stakeholders throughout the NCA process. A list of partners, minutes from meetings, and a list of events and resulting products is available at http://ncanet.usgcrp.gov.

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11. NCADAC: Federal Advisory Committee Draft Climate Assessment. National Climate Assessment and Development Advisory Committee. [Available online at http://ncadac.globalchange.gov]
12. USGCRP: National Climate Assessment: Opportunities for Engagement. [Available online at http://www.globalchange.gov/what-we-do/assessment/nca-activities]

APPENDIX 2 INFORMATION QUALITY ASSURANCE PROCESS

Summary of Information Quality Assurance Process for the Third National Climate Assessment Report

Throughout the process of drafting this National Climate Assessment, guidance was provided to contributors, authors, federal advisory committee members, and staff regarding the requirements of the Information Quality Act (IQA).

In September 2011, *Preliminary Guidance on Information Quality Assurance in Preparing Technical Input for the National Climate Assessment (NCA)*[1] was made available on the U.S. Global Change Research Program's (USGCRP) website along with other information for those interested in submitting technical input to the NCA in response to the Request for Information posted in the Federal Register on July 13, 2011.[2] This frequently asked questions-style document provided preliminary guidance regarding information quality for use by teams who submitted Expressions of Interest and Technical Inputs for use in the NCA.

In November 2011, the National Climate Assessment and Development Advisory Committee (NCADAC) approved the *General Principles Used in the Development of Guidance for Assuring Information Quality in the National Climate Assessment*.[3] The *Principles* were used by the NCADAC to draft guidance for all Convening Lead Authors (CLAs), Lead Authors, Review Editors, NCADAC, and Government Agencies and Reviewers to assure that information used in the NCA production was of appropriate quality relative to its intended use.

Two tools were developed – a set of questions and a flowchart – to assist the authors and reviewers in determining whether and how to use potential source material in the NCA within the requirements of the IQA. These tools (collectively, *Guidance on Information Quality Assurance to Chapter Authors of the National Climate Assessment: Question Tools*) were approved by the NCADAC and introduced to the CLAs at workshops. They have been available on the USGCRP website since February 2012.[4] The *Guidance* requires consideration of the following criteria for each source of information used in the Third NCA Report:

- Utility: Is the particular source important to the topic of your chapter?
- Transparency and traceability: Is the source material identifiable and publicly available?
- Objectivity: Why and how was the source material created? Is it accurate and unbiased?
- Information integrity and security: Will the source material remain reasonably protected and intact over time?

References

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Climate Change Impacts in the United States

APPENDIX 3 CLIMATE SCIENCE SUPPLEMENT

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Recommended Citation for Chapter

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Appendix 3: Climate Science Supplement. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 735-789. doi:10.7930/J0KS6PHH.

On the Web: http://nca2014.globalchange.gov/report/appendices/climate-science-supplement

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

APPENDIX 3 CLIMATE SCIENCE

Supplemental Messages

1. **Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.**
2. **Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.**
3. **Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.**
4. **Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The "fingerprints" of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.**
5. **Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.**
6. **Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.**
7. **Scientific understanding of observed temperature changes in the United States has greatly improved, confirming that the U.S. is warming due to heat-trapping gas emissions, consistent with the climate change observed globally.**
8. **Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.**
9. **Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate change's effects on other types of extreme events continues.**
10. **Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.**

11. Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.

12. Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

This appendix provides further information and discussion on climate science beyond that presented in Ch. 2: Our Changing Climate. Like the chapter, the appendix focuses on the observations, model simulations, and other analyses that explain what is happening to climate at the national and global scales, why these changes are occurring, and how climate is projected to change throughout this century. In the appendix, however, more information is provided on attribution, spatial and temporal detail, and physical mechanisms than could be covered within the length constraints of the main chapter.

As noted in the main chapter, changes in climate, and the nature and causes of these changes, have been comprehensively discussed in a number of other reports, including the 2009 assessment: *Global Climate Change Impacts in the United States*[1] and the global assessments produced by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Academy of Sciences. This appendix provides an updated discussion of global change in the first few supplemental messages, followed by messages focusing on the changes having the greatest impacts (and potential impacts) on the United States. The projections described in this appendix are based, to the extent possible, on the CMIP5 model simulations. However, given the timing of this report relative to the evolution of the CMIP5 archive, some projections are necessarily based on CMIP3 simulations. (See Supplemental Message 5 for more on these simulations and related future scenarios).

Supplemental Message 1.

Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.

The Earth's climate has long been known to change in response to natural external forcings. These include variations in the energy received from the sun, volcanic eruptions, and changes in the Earth's orbit, which affects the distribution of sunlight across the world. The Earth's climate is also affected by factors that are internal to the climate system, which are the result of complex interactions between the atmosphere, ocean, land surface, and living things (see Supplemental Message 3). These internal factors include natural modes of climate system variability, such as the El Niño/Southern Oscillation.

Natural changes in external forcings and internal factors have been responsible for past climate changes. At the global scale, over multiple decades, the impact of external forcings on temperature far exceeds that of internal variability (which is less than 0.5°F).[2] At the regional scale, and over shorter time periods, internal variability can be responsible for much larger changes in temperature and other aspects of climate. Today, however, the picture is very different. Although natural factors still affect climate, human activities are now the primary cause of the current warming: specifically, human activities that increase atmospheric levels of carbon dioxide (CO_2) and other heat-trapping gases and various particles that, depending on the type of particle, can have either a heating or cooling influence on the atmosphere.

The greenhouse effect is key to understanding how human activities affect the Earth's climate. As the sun shines on the Earth, the Earth heats up. The Earth then re-radiates this heat back to space. Some gases, including water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O), absorb some of the heat given off by the Earth's surface and lower atmosphere. These heat-trapping gases then radiate energy back toward the surface, effectively trapping some of the heat inside the climate system. This greenhouse effect is a natural process, first recognized in 1824 by the French mathematician and physicist Joseph Fourier[3] and confirmed by British scientist John Tyndall in a series of experiments starting in 1859.[4] Without this natural greenhouse effect (but assuming the same albedo, or reflectivity, as today), the average surface temperature of the Earth would be about 60°F colder.

Today, however, the natural greenhouse effect is being artificially intensified by human activities. Burning fossil fuels (coal,

Human Influence on the Greenhouse Effect

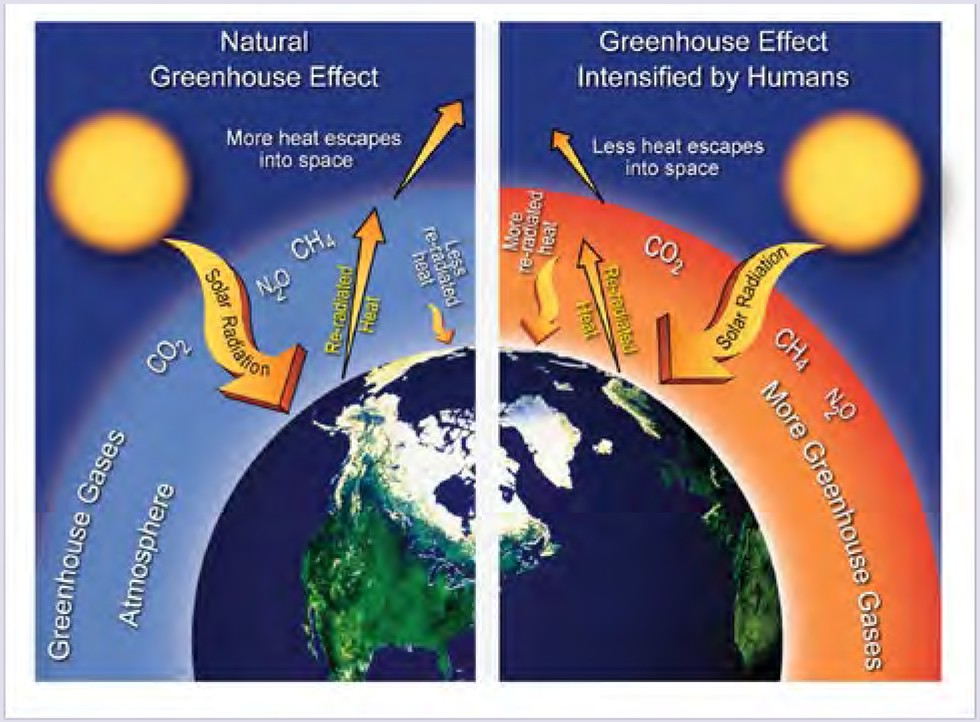


Figure 1. Left: A stylized representation of the natural greenhouse effect. Most of the sun's radiation reaches the Earth's surface. Naturally occurring heat-trapping gases, including water vapor, carbon dioxide, methane, and nitrous oxide, do not absorb the short-wave energy from the sun but do absorb the long-wave energy re-radiated from the Earth, keeping the planet much warmer than it would be otherwise. **Right**: In this stylized representation of the human-intensified greenhouse effect, human activities, predominantly the burning of fossil fuels (coal, oil, and gas), are increasing levels of carbon dioxide and other heat-trapping gases, increasing the natural greenhouse effect and thus Earth's temperature. (Figure source: modified from National Park Service[5]).

Earth's Energy Balance

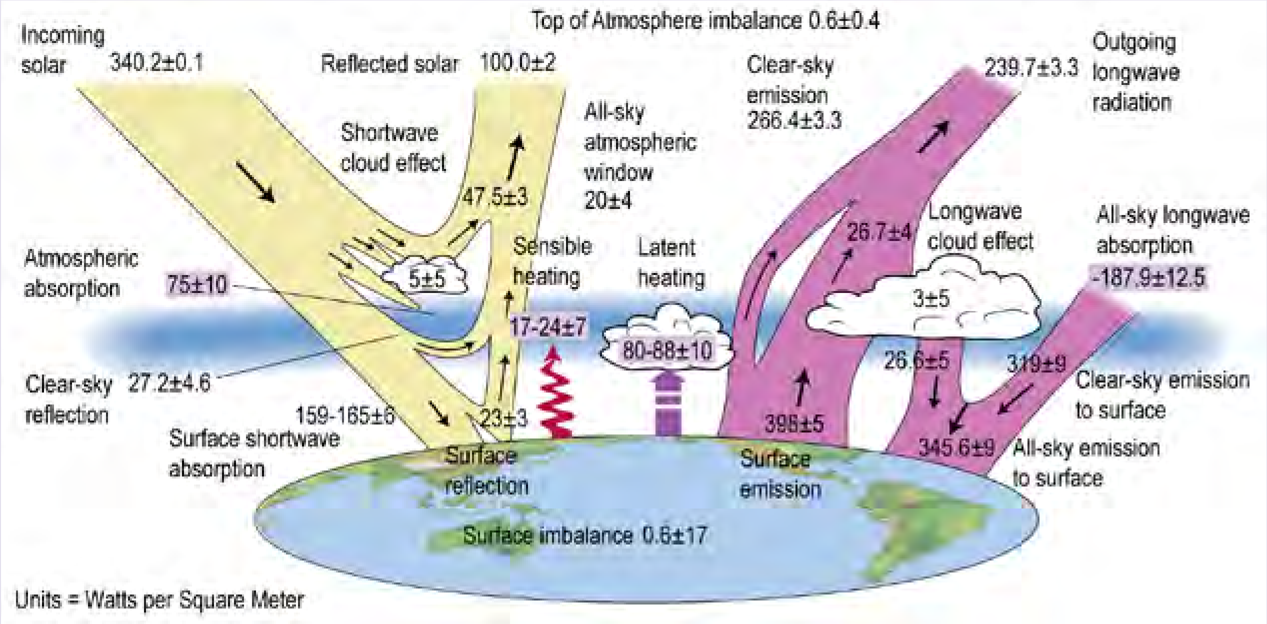


Figure 2. This figure summarizes results of measurements taken from satellites of the amount of energy coming in to and going out of Earth's climate system. It demonstrates that our scientific understanding of how the greenhouse effect operates is, in fact, accurate, based on real world measurements. (Figure source: modified from Stephens et al. 2012[6]).

Carbon Emissions in the Industrial Age

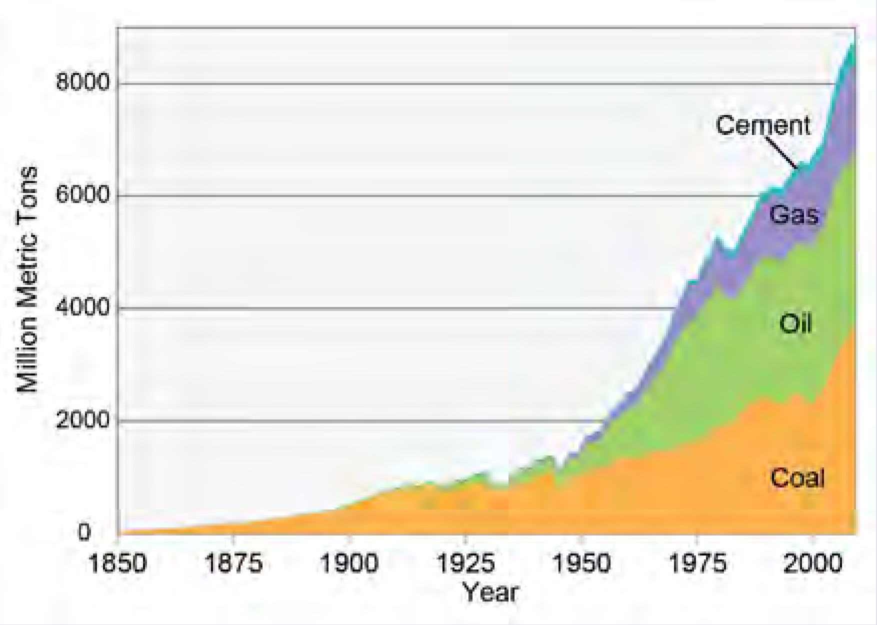


Figure 3. Global carbon emissions from burning coal, oil, and gas and producing cement (1850-2009). These emissions account for about 80% of the total emissions of carbon from human activities, with land-use changes (like cutting down forests) accounting for the other 20% in recent decades (Data from Boden et al. 2012[7]).

oil, and natural gas), clearing forests, and other human activities produce heat-trapping gases. These gases accumulate in the atmosphere, as natural removal processes are unable to keep pace with increasing emissions. Increasing atmospheric levels of CO_2, CH_4, and N_2O (and other gases and some types of particles like soot) from human activities increase the amount of heat trapped inside the Earth system. This human-caused intensification of the greenhouse effect is the primary cause of observed warming in recent decades.

Carbon dioxide has been building up in the Earth's atmosphere since the beginning of the industrial era in the mid-1700s. Emissions and atmospheric levels, or concentrations, of other important heat-trapping gases – including methane, nitrous oxide, and halocarbons – have also increased because of human activities. While the atmospheric concentrations of these gases are relatively small compared to those of molecular oxygen or nitrogen, their ability to trap heat is extremely strong. The human-induced increase in atmospheric levels of carbon dioxide and other heat-trapping gases is the main reason the planet has warmed over the past 50 years and has been an important factor in climate change over the past 150 years or more.

Carbon dioxide levels in the atmosphere are currently increasing at a rate of 0.5% per year. Atmospheric levels measured at Mauna Loa in Hawai'i and at other sites around the world reached 400 parts per million in 2013, higher than the Earth has experienced in over a million years. Globally, over the past several decades, about 78% of carbon dioxide emissions has come from burning fossil fuels, 20% from deforestation and other agricultural practices, and 2% from cement production. Some of the carbon dioxide emitted to the atmosphere is absorbed by the oceans, and some is absorbed by vegetation.

Heat-Trapping Gas Levels

2000 Years of Heat Trapping Gases

CO_2 1958–2013

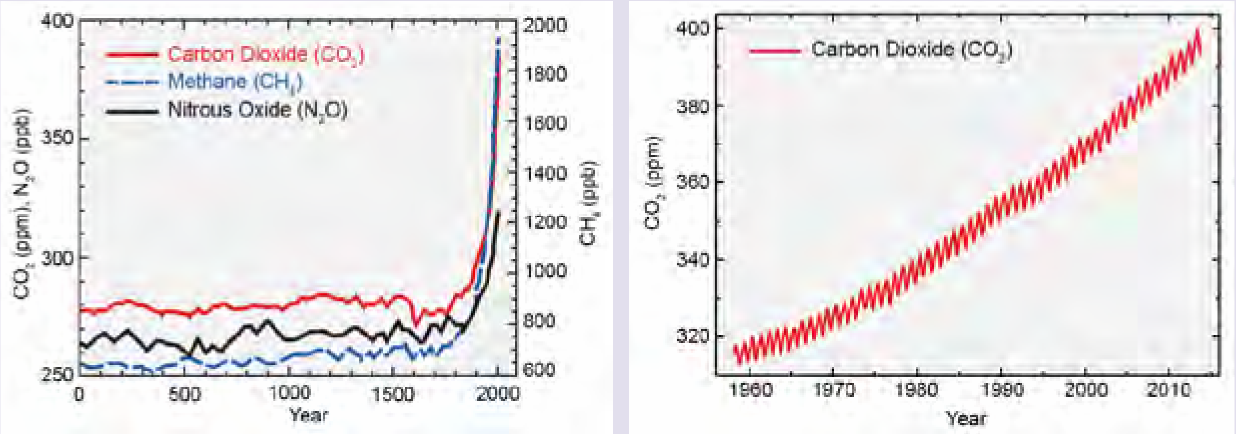


Figure 4. Present-day atmospheric levels of carbon dioxide, methane, and nitrous oxide are notably higher than their pre-industrial averages of 280, 0.7, and 0.27 parts per million (ppm) by volume, respectively (left). Air sampling data from 1958 to 2013 show long-term increases due to human activities as well as short-term variations due to natural biogeochemical processes and seasonal vegetation growth (right). (Figure sources: (left) Forster et al. 2007;[8] (right) Scripps Institution of Oceanography and NOAA Earth Systems Research Laboratory).

Atmospheric Carbon Dioxide Levels

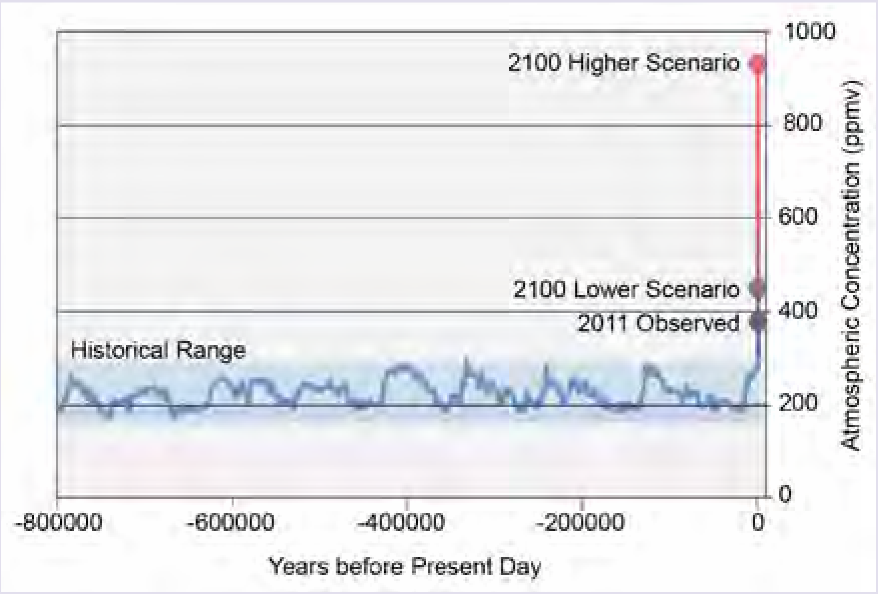


Figure 5. Air bubbles trapped in an Antarctic ice core extending back 800,000 years document the atmosphere's changing carbon dioxide concentration. Over long periods, natural factors have caused atmospheric CO_2 concentrations to vary between about 170 to 300 parts per million (ppm). As a result of human activities since the Industrial Revolution, CO_2 levels have increased to 400 ppm, higher than any time in at least the last one million years. By 2100, additional emissions from human activities are projected to increase CO_2 levels to 420 ppm under a very low scenario, which would require immediate and sharp emissions reductions (RCP 2.6), and 935 ppm under a higher scenario, which assumes continued increases in emissions (RCP 8.5). This figure shows the historical composite CO_2 record based on measurements from the EPICA (European Project for Ice Coring in Antarctica) Dome C and Dronning Maud Land sites and from the Vostok station. Data from Lüthi et al. 2008[9] (664-800 thousand years [kyr] ago, Dome C site); Siegenthaler et al. 2005[10] (393-664 kyr ago, Dronning Maud Land); Pépin 2001, Petit et al. 1999, and Raynaud 2005[11] (22-393 kyr ago, Vostok); Monnin et al. 2001[12] (0-22 kyr ago, Dome C); and Meinshausen et al. 2011[13] (future projections from RCP 2.6 and 8.5).

About 45% of the carbon dioxide emitted by human activities in the last 50 years is now stored in the oceans and vegetation. The remainder has built up in the atmosphere, where carbon dioxide levels have increased by about 40% relative to pre-industrial levels.

Methane levels in the atmosphere have increased due to human activities, including agriculture, with livestock producing methane in their digestive tracts, and rice farming producing it via bacteria that live in the flooded fields; mining coal, extraction and transport of natural gas, and other fossil fuel-related activities; and waste disposal including sewage and decomposing garbage in landfills. On average, about 55% to 65% of the emissions of atmospheric methane now come from human activities.[14,15] Atmospheric concentrations of methane leveled off from 1999-2006 due to temporary decreases in both human and natural sources,[14,15] but have been increasing again since then. Since preindustrial times, methane levels have increased by 250% to their current levels of 1.85 ppm.

Other greenhouse gases produced by human activities include ***nitrous oxide, halocarbons, and ozone.***

Nitrous oxide levels are increasing, primarily as a result of fertilizer use and fossil fuel burning. The concentration of nitrous oxide has increased by about 20% relative to pre-industrial times.

Halocarbons are manufactured chemicals produced to serve specific purposes, from aerosol spray propellants to refrigerant coolants. One type of halocarbon, long-lived chlorofluorocarbons (CFCs), was used extensively in refrigeration, air conditioning, and for various manufacturing purposes. However, in addition to being powerful heat-trapping gases, they are also responsible for depleting stratospheric ozone. Atmospheric levels of CFCs are now decreasing due to actions taken by countries under the Montreal Protocol, an international agreement designed to protect the ozone layer. As emissions and atmospheric levels of halocarbons continue to decrease, their effect on climate will also shrink. However, some of the replacement compounds are hydrofluorocarbons (HFCs), which are potent heat-trapping gases, and their concentrations are increasing.

Over 90% of the ozone in the atmosphere is in the stratosphere, where it protects the Earth from harmful levels of ultraviolet radiation from the sun. In the lower atmosphere, however, ozone is an air pollutant and also an important heat-trapping gas. Upper-atmosphere ozone levels have decreased because of human emissions of CFCs and other halocarbons. However, lower-atmosphere ozone levels have increased because of human activities, including transportation and manufacturing. These produce what are known as ozone precursors: air pollutants that react with sunlight and other chemicals to produce ozone. Since the late 1800s, average levels of ozone in the lower atmosphere have increased by more than 30%.[16] Much higher increases have been observed in areas with high levels of air pollution, and smaller increases in remote locations where the air has remained relatively clean.

Human activities can also produce tiny atmospheric particles, including dust and soot. For example, coal burning produces sulfur gases that form particles in the atmosphere. These sulfur-containing particles reflect incoming sunlight away from the Earth, exerting a cooling influence on Earth's surface.

Another type of particle, composed mainly of soot, or black carbon, absorbs incoming sunlight and traps heat in the atmosphere, warming the Earth.

In addition to their direct effects, these particles can affect climate indirectly by changing the properties of clouds. Some encourage cloud formation because they are ideal surfaces on which water vapor can condense to form cloud droplets. Some can also increase the number, but decrease the average size of cloud droplets when there is not enough water vapor compared to the number of particles available, thus creating brighter clouds that reflect energy from the sun away from the Earth, resulting in an overall cooling effect. Particles that absorb energy encourage cloud droplets to evaporate by warming the atmosphere. Depending on their type, increasing amounts of particles can either offset or increase the warming caused by increasing levels of greenhouse gases. At the scale of the planet, the net effect of these particles is to offset between 20% and 35% of the warming caused by heat-trapping gases.

The effects of all of these greenhouse gases and particles on the Earth's climate depend in part on how long they remain in the atmosphere. Human-induced emissions of carbon dioxide have already altered atmospheric levels in ways that will persist for thousands of years. About one-third of the carbon dioxide emitted in any given year remains in the atmosphere 100 years later. However, the impact of past human emissions of carbon dioxide on the global carbon cycle will endure for tens of thousands of years. Methane lasts for approximately a decade before it is removed through chemical reactions. Particles, on the other hand, remain in the atmosphere for only a few days to several weeks. This means that the effects of any human actions to reduce particle emissions can show results nearly immediately. It may take decades, however, before the results of human actions to reduce long-lived greenhouse gas emissions can be observed. Some recent studies[17] examine various means for reducing near-term changes in climate, for example, by reducing emissions of short-lived gases like methane and particles like black carbon (soot). These approaches are being explored as ways to reduce the rate of short-term warming while more comprehensive approaches to reducing carbon dioxide emissions (and hence the rate of long-term warming) are being implemented.

In addition to emissions of greenhouse gases, air pollutants, and particles, human activities have also affected climate by changing the land surface. These changes include cutting and burning forests, replacing natural vegetation with agriculture or cities, and large-scale irrigation. These transformations of the land surface can alter how much heat is reflected or absorbed by the surface, causing local and even regional warming or cooling. Globally, the net effect of these changes has probably been a slight cooling influence over the past 100 years.

Considering all known natural and human drivers of climate since 1750, a strong net warming from long-lived greenhouse gases produced by human activities dominates the recent climate record. This warming has been partially offset by increases in atmospheric particles and their effects on clouds. Two important natural external drivers also influence climate: the sun and volcanic eruptions. Since 1750, these natural external drivers are estimated to have had a small net warming influence, one that is much smaller than the human influence. Natural internal climate variations, such as El Niño events in

Relative Strengths of Warming and Cooling Influences

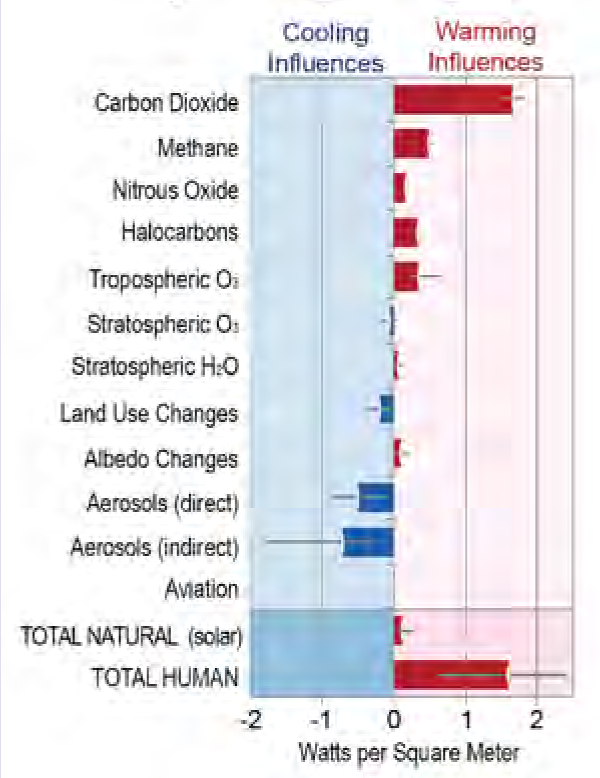


Figure 6. Different factors have exerted a warming influence (red bars) or a cooling influence (blue bars) on the planet. The warming or cooling influence of each factor is measured in terms of the change in radiative forcing in watts per square meter by 2005 relative to 1750. This figure includes all the major human-induced factors as well as the sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes is also natural, but is relatively short-lived and so is not included here. Aerosols refer to tiny particles, with their direct effects including, for example, the warming influence of black carbon (soot) and cooling influence of sulfate particles from coal burning. Indirect effects of aerosols include their effect on clouds. The net radiative influence from natural and human influences is a strong warming, predominantly from human activities. The thin lines on each bar show the range of uncertainty. (Figure source: adapted from *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Figure 2.20 (A), Cambridge University Press[15]).

the Pacific Ocean, have also influenced regional and global climate. Several other modes of internal natural variability have been identified, and their effects on climate are superimposed on the effects of human activities, the sun, and volcanoes.

During the last three decades, direct observations indicate that the sun's energy output has decreased slightly. The two major volcanic eruptions of the past 30 years have had short-term cooling effects on climate, lasting two to three years. Thus, natural factors cannot explain the warming of recent decades; in fact, their net effect on climate has been a slight cooling influence over this period. In addition, the changes occurring now are very rapid compared to the major changes in climate over at least the last several thousand years.

It is not only the direct effects from human emissions that affect climate. These direct effects also trigger a cascading set of feedbacks that cause indirect effects on climate – acting to increase or dampen an initial change. For example, water vapor is the single most important gas responsible for the natural greenhouse effect. Together, water vapor and clouds account for between 66% and 80% of the natural greenhouse effect.[18] However, the amount of water vapor in the atmosphere depends on temperature; increasing temperatures increase the amount of water vapor. This means that the response of water vapor is an internal feedback, not an external forcing of the climate.

Observational evidence shows that, of all the external forcings, an increase in atmospheric CO_2 concentration is the most important factor in increasing the heat-trapping capacity of the atmosphere. Carbon dioxide and other gases, such as methane and nitrous oxide, do not condense and fall out of the atmosphere, whereas water vapor does (for example, as rain or snow). Together, heat-trapping gases other than water vapor account for between 26% and 33% of the total greenhouse effect,[18] but are responsible for most of the changes in climate over recent decades. This is a range, rather than a single number, because some of the absorption effects of water vapor overlap with those of the other important gases. Without the heat-trapping effects of carbon dioxide and the other non-water vapor greenhouse gases, climate simulations indicate that the greenhouse effect would not function, turning the Earth into a frozen ball of ice.[19]

The average conditions and the variability of the Earth's climate are critical to all aspects of human and natural systems on the planet. Human society has become increasingly complex and dependent upon the climate system and its behavior. National and global infrastructures, economies, agriculture, and ecosystems are adapted to the present climate state, which from a geologic timescale perspective has been remarkably stable for the past several thousand years. Any significant perturbation, in either direction, would have substantial impacts upon both human society and the natural world. The magnitude of the human influence on climate and the rate of change raise concerns about the ability of ecosystems and human systems to successfully adapt to future changes.

Supplemental Message 2.

Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.

There are many types of observations that can be used to detect changes in climate and determine what is causing these changes. Thermometer and other instrument-based surface weather records date back hundreds of years in some locations. Air temperatures are measured at fixed locations over land and with a mix of predominantly ship- and buoy-based measurements over the ocean. By 1850, a sufficiently extensive array of land-based observing stations and ship-borne observations had accumulated to begin tracking global average temperature. Measurements from weather balloons began in the early 1900s, and by 1958 were regularly taken around the world. Satellite records beginning in the 1970s provide additional perspectives, particularly for remote areas such as the Arctic that have limited ground-based observations. Satellites also provided new capabilities for mapping precipitation and upper air temperatures. Climate "proxies" – biological or physical records ranging from tree rings to ice cores that correlate with aspects of climate – provide further evidence of past climate that can stretch back hundreds of thousands of years.

These diverse datasets have been analyzed by scientists and engineers from research teams around the world in many different ways. The most high-profile indication of the changing climate is the surface temperature record, so it has received the most attention. Spatial coverage, equipment, methods of observation, and many other aspects of the measurement record have changed over time, so scientists identify and adjust for these changes. Independent research groups have looked at the surface temperature record for land[21] and ocean[22] as well as land and ocean combined.[23,24] Each group takes a different approach, yet all agree that it is unequivocal that the planet is warming.

There has been widespread warming over the past century. Not every region has warmed at the same pace, however,

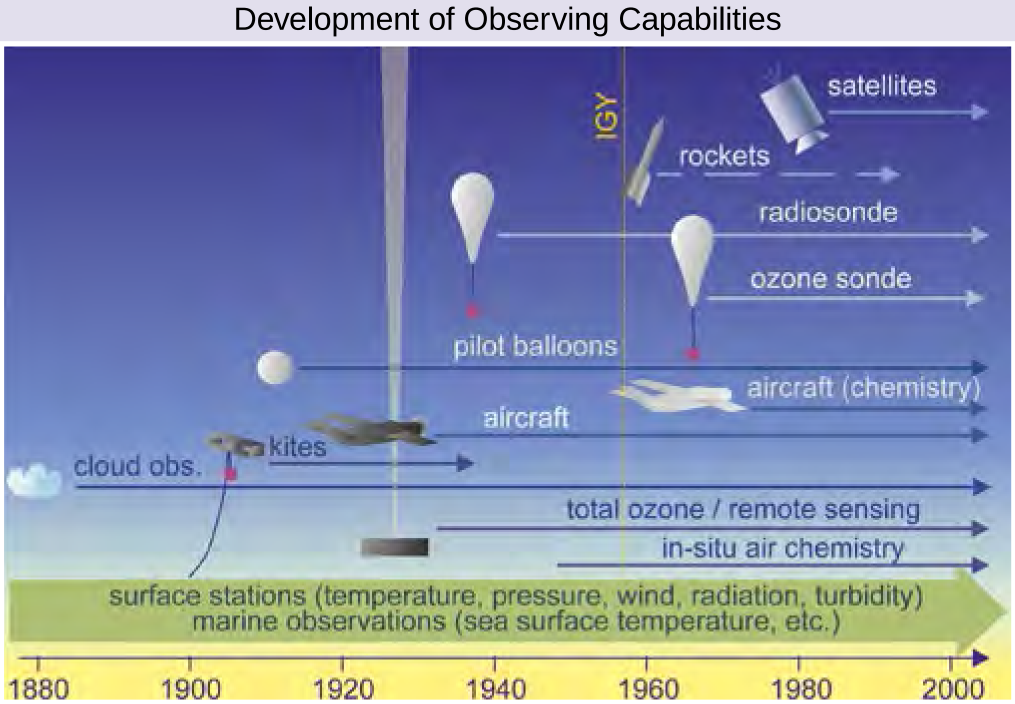


Figure 7. Changes in the mix and increasing diversity of technologies used to observe climate (IGY is the International Geophysical Year). (Figure source: adapted from Brönnimann et al. 2007[20]).

and a few regions, such as the North Atlantic Ocean (Figure 9) and some parts of the U.S. Southeast (Ch. 2: Our Changing Climate, Figure 2.7), have even experienced cooling over the last century as a whole, though they have warmed over recent decades. This is due to the stronger influence of internal variability over smaller geographic regions and shorter time scales, as mentioned in Supplemental Message 1 and discussed in more detail in Supplemental Message 3. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have seen greater warming in response to accelerating increases in heat-trapping gas concentrations, particularly at high northern latitudes, and over land as compared to ocean.

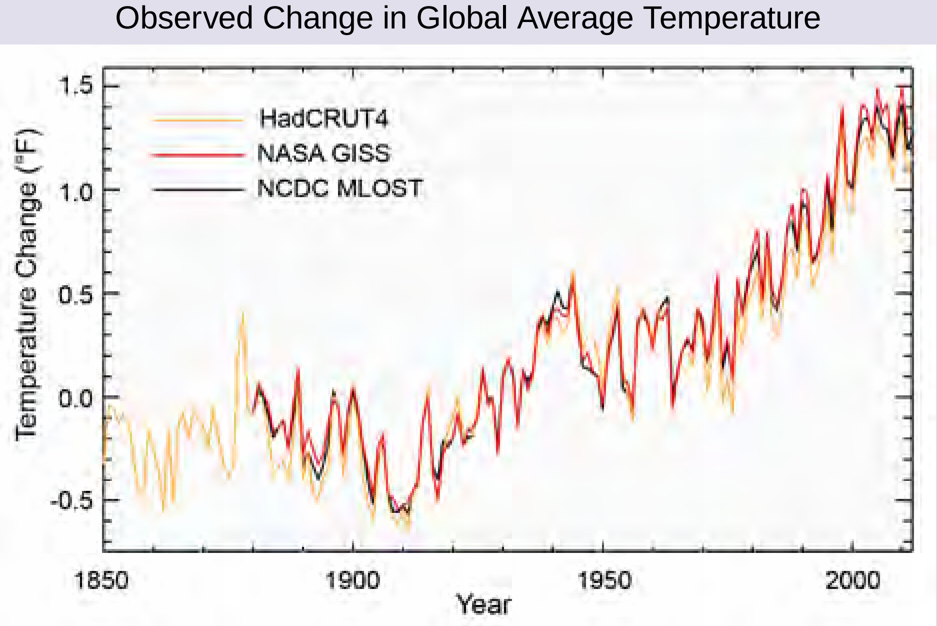


Figure 8. Three different global surface temperature records all show increasing trends over the last century. The lines show annual differences in temperature relative to the 1901-1960 average. Differences among data sets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Figure source: NOAA NCDC / CICS-NC).

Temperature Trends: Past Century, Past 30+ Years

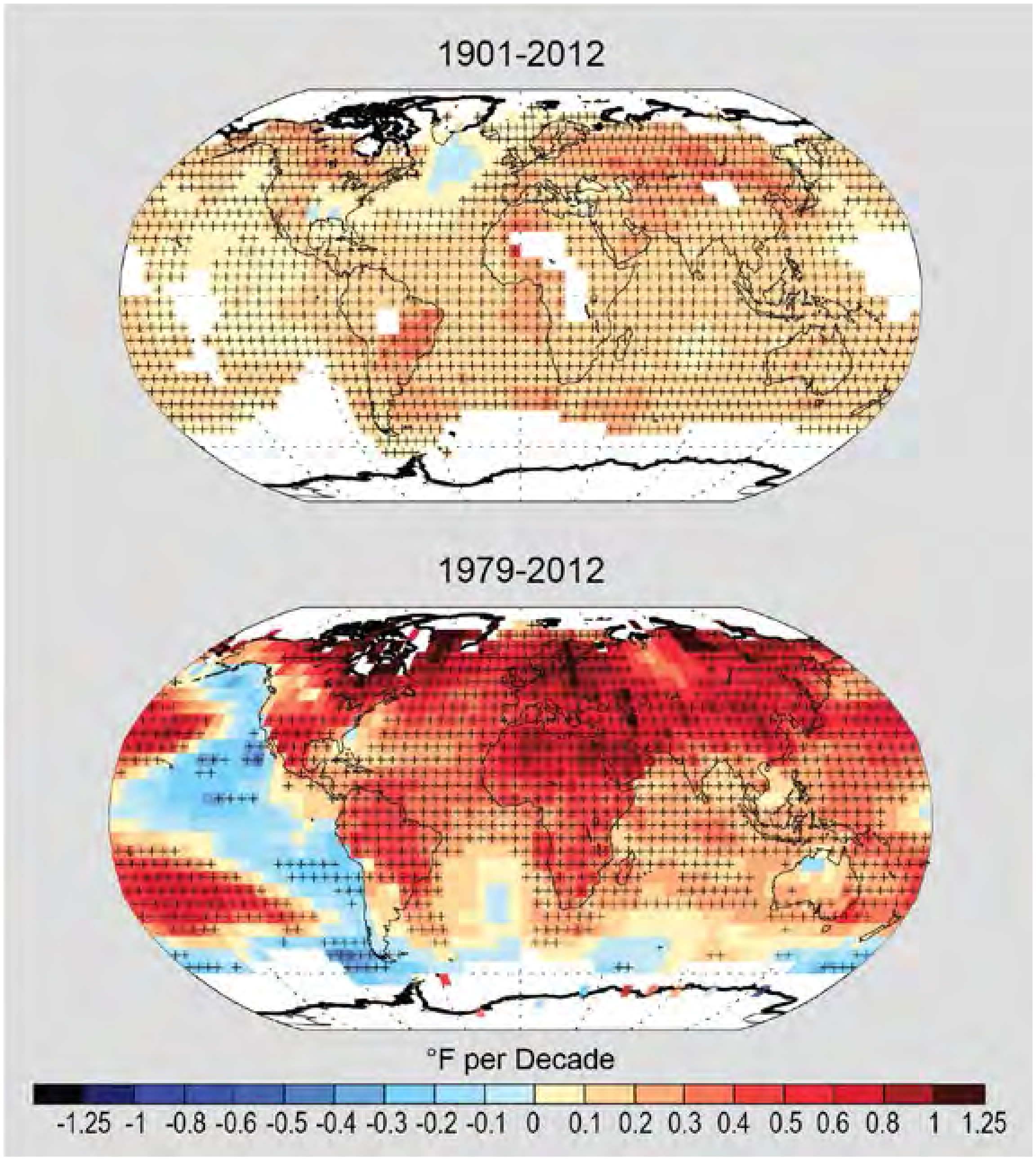


Figure 9. Surface temperature trends for the period 1901-2012 (top) and 1979-2012 (bottom) from the National Climatic Data Center's (NCDC) surface temperature product. The relatively coarse resolution of these maps does not capture the finer details associated with mountains, coastlines, and other small-scale effects. (Figure source: updated from Vose et al. 2012[24]).

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been increasing because multiple lines of evidence all support this conclusion. Temperatures in the lower atmosphere and oceans have increased, as have sea level and near-surface humidity. Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. As with temperature, multiple research groups have analyzed each of these indicators and come to the same conclusion: all of these changes paint a consistent and compelling picture of a warming world.

Indicators of Warming from Multiple Data Sets

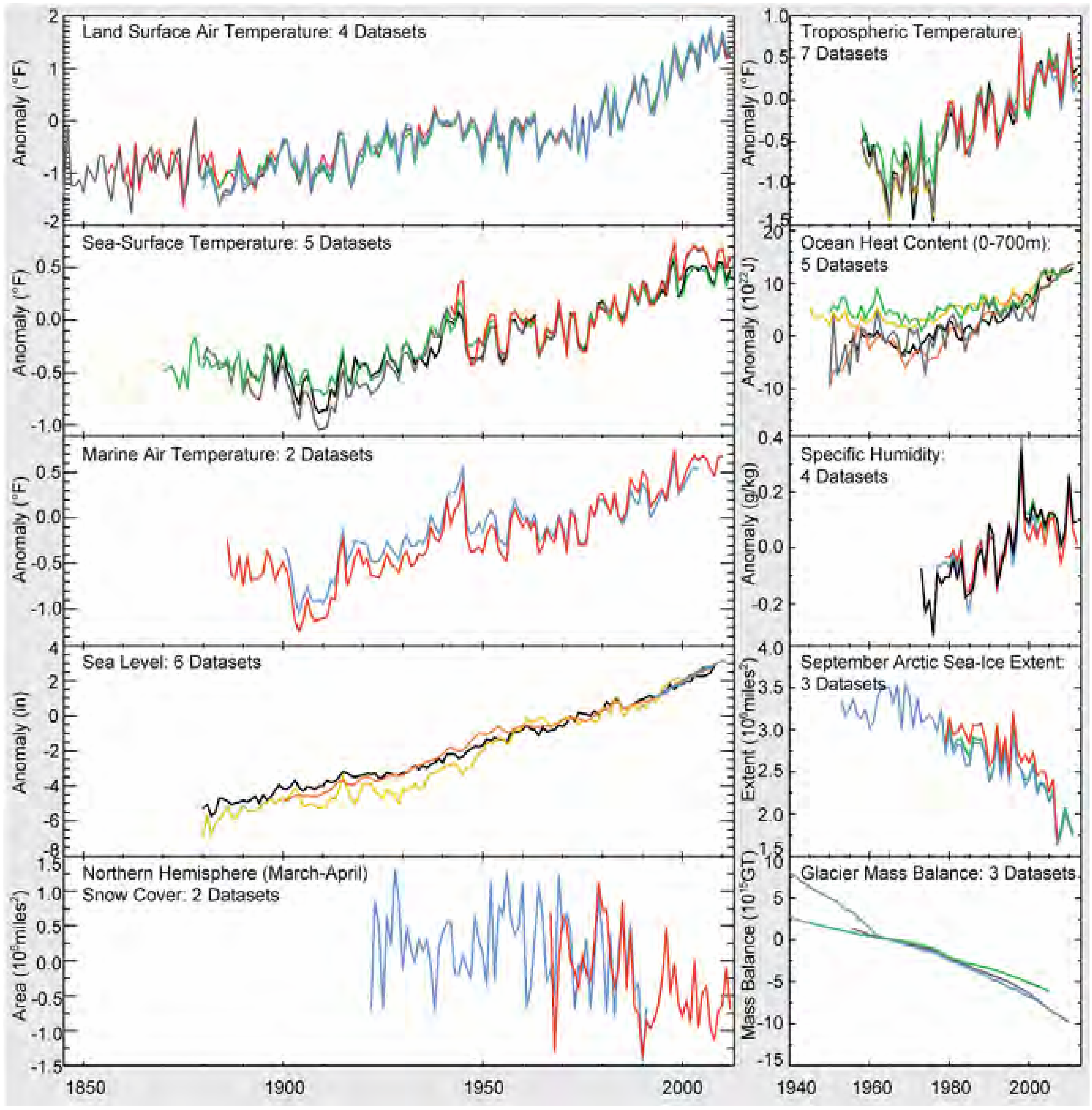


Figure 10. Observed changes, as analyzed by many independent groups in different ways, of a range of climate indicators. All of these are in fact changing as expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/. (Figure source: updated from Kennedy et al. 2010[25]).

Not all of the observed changes are directly related to temperature; some are related to the hydrological cycle (the way water moves cyclically among land, ocean, and atmosphere). Precipitation is perhaps the most societally relevant aspect of the hydrological cycle and has been observed over global land areas for over a century. However, spatial scales of precipitation are small (it can rain several inches in Washington, D.C., but not a drop in Baltimore) and this makes interpretation of the point-measurements difficult. Based upon a range of efforts to create global averages, it is likely that there has been little change in globally averaged precipitation since 1900. However, there are strong geographic trends including a likely increase in precipitation in Northern Hemisphere mid-latitude regions taken as a whole. In general, wet areas are getting wetter and dry areas are getting drier, consistent with an overall intensification of the hydrological cycle in response to global warming.

Analyses of past changes in climate during the period before instrumental records (referred to as paleoclimate) allow current changes in atmospheric composition, sea level, and climate (including extreme events), as well as future projections, to be placed in a broader perspective of past climate variability. A number of different reconstructions of the last 1,000 to 2,000 years[26,27] give a consistent picture of Northern Hemisphere temperatures, and in a few cases, global temperatures, over that time period. The analyses in the Northern Hemisphere indicate that the 1981 to 2010 period (including the last decade) was the warmest of at least the last 1,300 years and probably much longer.[28,29] A reconstruction going back 11,300 years ago[30] suggests that the last decade was warmer than at least 72% of global temperatures since the end of the last ice age 20,000 years ago. The observed warming of the last century has also apparently reversed a long-term cooling trend at mid- to high latitudes of the Northern Hemisphere throughout the last 2,000 years.

Other analyses of past climates going back millions of years indicate that past periods with high levels (400 ppm or greater) of CO_2 were associated with temperatures much higher than today's and with much higher sea levels.[31]

Precipitation Trends: Past Century, Past 30+ Years

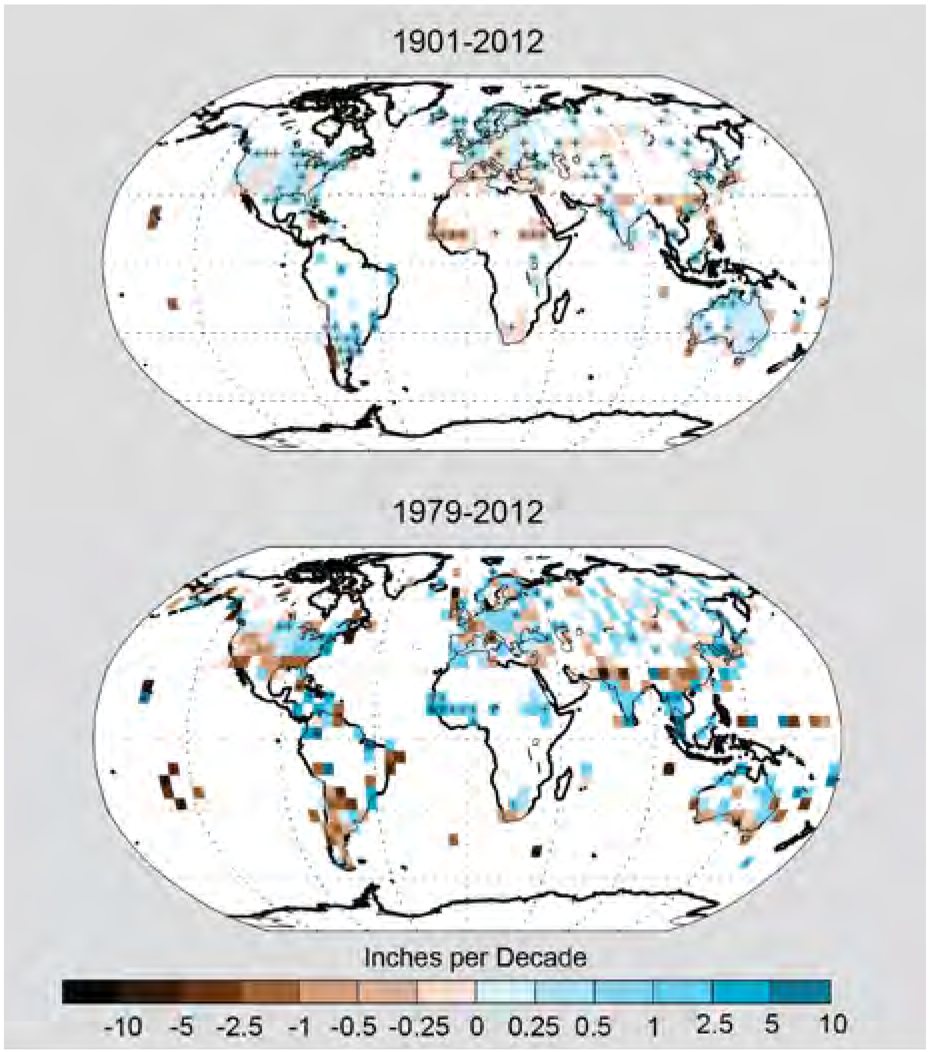


Figure 11. Global precipitation trends for the period 1901-2012 (top) and 1979-2012 (bottom). (Figure source: NOAA NCDC / CICS-NC).

1700 Years of Global Temperature Change from Proxy Data

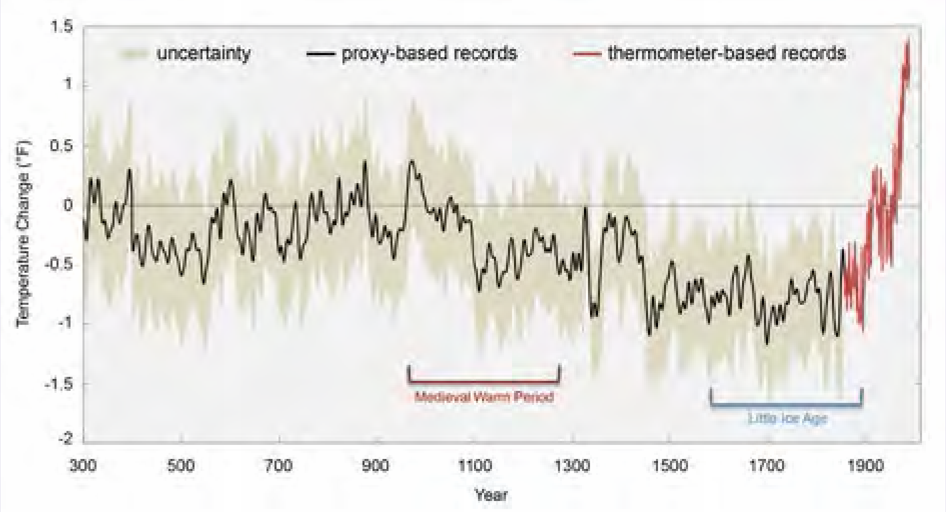


Figure 12. Changes in the temperature of the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961-1990 average temperature. These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years, and that the last decade (2001 to 2010) was the warmest decade on record. (Figure source: adapted from Mann et al. 2008[27]).

Supplemental Message 3.

Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.

Natural variations internal to the Earth's climate system can drive increases or decreases in global and regional temperatures, as well as affect precipitation and drought patterns around the world. Today, average temperature, precipitation, and other aspects of climate are determined by a combination of human-induced changes superimposed on natural variations in both internal and external factors such as the sun and volcanoes (see Supplemental Message 1). The relative magnitudes of the human and natural contributions to temperature and climate depend on both the time and spatial scales considered. The magnitude of the effect humans are having on global temperature specifically, and on climate in general, has been steadily increasing since the Industrial Revolution. At the global scale, the human influence on climate can be either masked or augmented by natural internal variations over timescales of a decade or so (for example, Tung and Zhou 2013[32]). At regional and local scales, natural variations have an even larger effect. Over longer periods of time, however, the influence of internal natural variability on the Earth's climate system is negligible; in other words, over periods longer than several decades, the net effect of natural variability tends to sum to zero.

There are many modes of natural variability within the climate system. Most of them involve cyclical exchanges of heat and energy between the ocean and atmosphere. They are manifested by recurring changes in sea surface temperatures, for example, or by surface pressure changes in the atmosphere. While many global climate models are able to simulate the spatial patterns of ocean and atmospheric variability associated with these modes, they are less able to capture the chaotic variability in the timescales of the different modes.[33]

The largest and most well-known mode of internal natural variability is the El Niño/Southern Oscillation or ENSO. This natural mode of variability was first identified as a warm current of ocean water off the coast of Peru, accompanied by a shift in pressure between two locations on either side of the Pacific Ocean. Although centered in the tropical Pacific, ENSO affects regional temperatures and precipitation around the world by heating or cooling the lower atmosphere in low latitudes, thereby altering pressure gradients aloft. These pressure gradients, in turn, drive the upper-level winds and the jet stream that dictates patterns of mid-latitude weather, as shown in Figure 13. In the United States, for example, the warm ENSO phase (commonly referred to as El Niño) is usually associated with heavy rainfall and flooding in California and the Southwest, but decreased precipitation in the Northwest.[34] El Niño conditions also tend to suppress Atlantic hurricane formation by increasing the amount of wind shear in the region where hurricanes form.[35] The cool ENSO phase (usually called

La Niña and El Niño Patterns

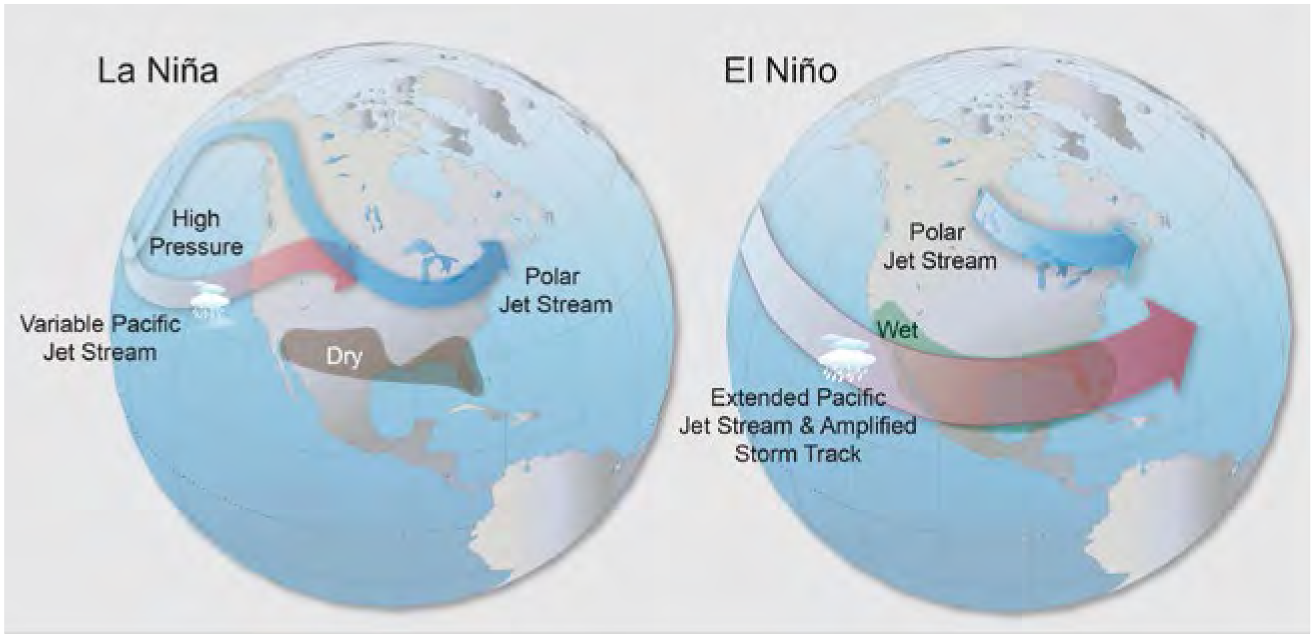


Figure 13. Typical January-March weather conditions and atmospheric circulation (jet streams shown by red and blue arrows) during La Niña and El Niño conditions. Cloud symbols show areas that are wetter than normal. During La Niña, winters tend to be unusually cold in eastern Alaska and western Canada, and dry throughout the southern United States. El Niño leads to unusually warm winter conditions in the northern U.S. and wetter than average conditions across the southern U.S. (Figure source: NOAA).

Warming Trend and Effects of El Niño/La Niña
GISTEMP Land-Ocean Index

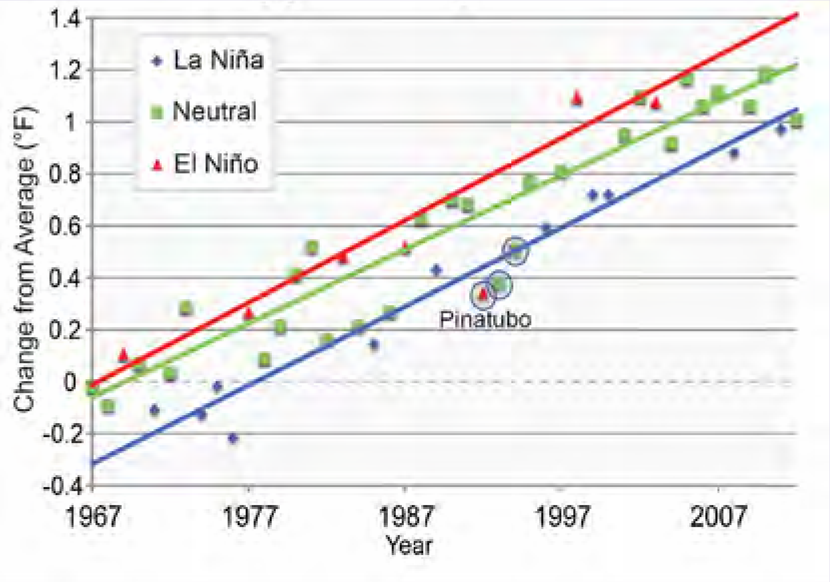


Figure 14. Trends in globally and annually averaged temperature when considering whether it was an El Niño year, a La Niña year, or a neutral year (no El Niño or La Niña event). The average global temperature is 0.4ºF higher in El Niño years than in La Niña years. However, all trends show the same significant increase in temperature over the past 45 years. The years for the short-term cooling effect following the Mt. Pinatubo volcanic eruption are not included in the trends. (Figure source: adapted from John Nielsen-Gammon 2012.[38] Data from NASA GISS temperature dataset[39] and Climate Prediction Center Niño 3.4 index[40]).

La Niña) is associated with dry conditions in the Central Plains,[36] as well as a more active Atlantic hurricane season. Although these and other conditions are typically associated with ENSO, no two ENSO events are exactly alike.

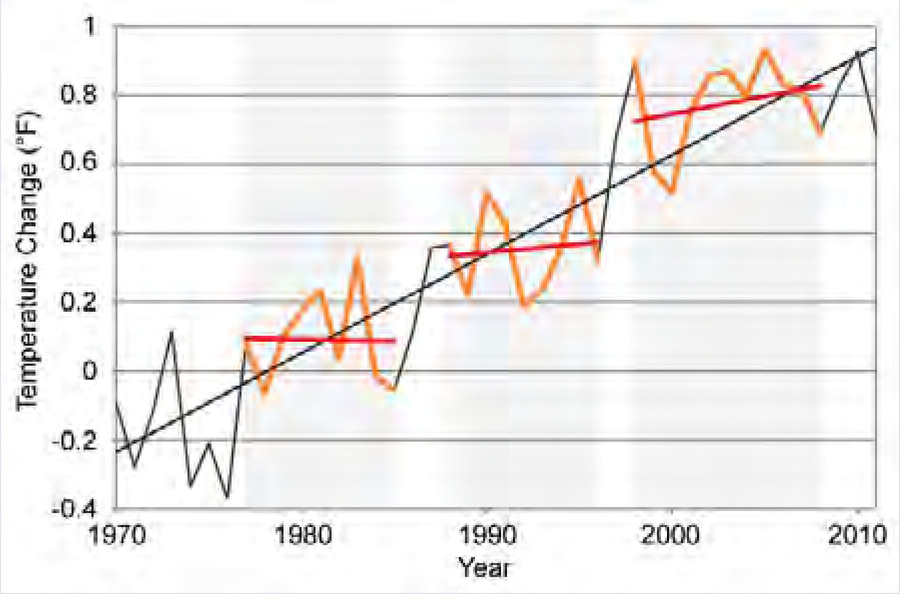
Natural modes of variability such as ENSO can also affect global temperatures. In general, El Niño years tend to be warmer than average and La Niña years, cooler. The strongest El Niño event recorded over the last hundred years occurred in 1998. Superimposed on the long-term increase in global temperatures due to human activities, this event caused record high global temperatures. After 1998, the El Niño event subsided, resulting in a slowdown in the temperature increase since 1998. Overall, however, years in which there are El Niño, La Niña, or neutral conditions all show similar long-term warming trends in global temperature (see Figure 14).

Natural modes of variability like ENSO are not necessarily stationary. For example, there appears to have been a shift in the pattern and timing of ENSO in the mid-1970s, with the location of the warm water pool shifting from the eastern to the central Pacific and the frequency of events increasing. Paleoclimate studies using tree rings show that ENSO activity over the last 100 years has been the highest in the last 500 years,[37] and both paleoclimate and modeling studies suggest that global temperature increases may interact with natural variability in ways that are difficult to predict. Climate models can simulate the statistical behavior of these variations in temperature trends. For example, models can project whether some phenomena will increase or decrease in frequency, but cannot predict the exact timing of particular events far into the future.

There are other natural modes of variability in the climate system. For example, the North Atlantic Oscillation is frequently linked to variations in winter snowfall along the Atlantic seaboard. The Pacific Decadal Oscillation was first identified as a result of its effect on the Pacific salmon harvest. The influence of these and other natural variations on global temperatures is generally less than ENSO, but local influences may be large.

A combination of natural and human factors explains regional "warming holes" where temperatures actually decreased for several decades in the middle to late part of the last century at a few locations around the world. In the United States, for example, the Southeast and parts of the Great Plains and Midwest regions did not show much warming over that time period, though they have warmed in recent decades. Explanations include increased cloud cover and precipitation,[41] increased small particles from coal burning, natural factors related to forest re-growth,[42] decreased heat flux due to irrigation,[43] and multi-decade variability in North Atlantic and tropical Pacific sea surface temperatures.[44,45] The importance of tropical Pacific and Atlantic sea surface temperatures on temperature and precipitation variability over the central U.S. has been particularly highlighted by many studies. Over the next few decades, as the multi-decadal tropical Pacific Ocean cycle continues its effect on sea surface temperatures, the U.S. Southeast could warm at a rate that is faster than the global average.[45]

At the global scale, natural variability will continue to modify the long-term trend in global temperature due to human activities, resulting in greater and lesser trends over relatively short time scales. Interactions among various components of the Earth's climate system produce patterns of natural variability that can be chaotic, meaning that they are sensitive to the initial conditions of the climate system. Global climate models simulate natural variability with varying degrees of realism, but the timing of these random variations differs among models and cannot be expected to coincide with those of the actual climate system. Over climatological time periods, however, the net effect of natural internal variability on the global climate



Long-Term Warming and Short-Term Variation

Figure 15. Observations of global mean surface air temperature show that although there can be short periods with little or even no significant upward trend (red trend lines in shaded areas), global temperature continues to rise unabated over long-term climate timescales (black trend line). The recent period, 1998-2012, is another example of a short-term pause embedded in the underlying warming trend. The differences between short-term trends and the underlying (long-term) trend are often associated with modes of natural variability such as El Niño and La Niña that redistribute heat between the ocean and atmosphere. (Data from NOAA NCDC).

tends to average to zero. For example, there can be warmer years due to El Niño (such as 1998) and cooler years due to La Niña (such as 2011), but over multiple decades the net effect of natural variability on uncertainty in global temperature and precipitation projections is small.

Averaging (or compositing) of projections from different models smooths out the randomly occurring natural variations in the different models, leaving a clear signal of the long-term externally forced changes in climate, not weather. In this report, all future projections are averaged over 20- to 30-year time periods.

Supplemental Message 4.

Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The "fingerprints" of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.

Determining the causes of climate changes is a field of research known as "detection and attribution." *Detection* involves identifying a climate trend or event (for instance, long-term surface air temperature trends, or a particularly extreme heat wave) that is strikingly outside the norm of natural variations in the climate system. Similar to conducting forensic analysis on evidence from a crime scene, *attribution* involves considering the possible causes of an observed event or change, and identifying which factor(s) are responsible.

Detection and attribution studies use statistical analyses to identify the causes of observed changes in temperature, precipitation, and other aspects of climate. They do this by trying to match the complex "fingerprint" of the observed climate system behavior to a set of simulated changes in climate that would be caused by different forcings.[46] Most approaches consider not only global but also regional patterns of changes over time.

Climate simulations are used to test hypotheses regarding the causes of observed changes. First, simulations that include changes in both natural and human forcings that may cause climate changes, such as changes in energy from the sun and increases in heat-trapping gases, are used to characterize what

Detection and Attribution as Forensics

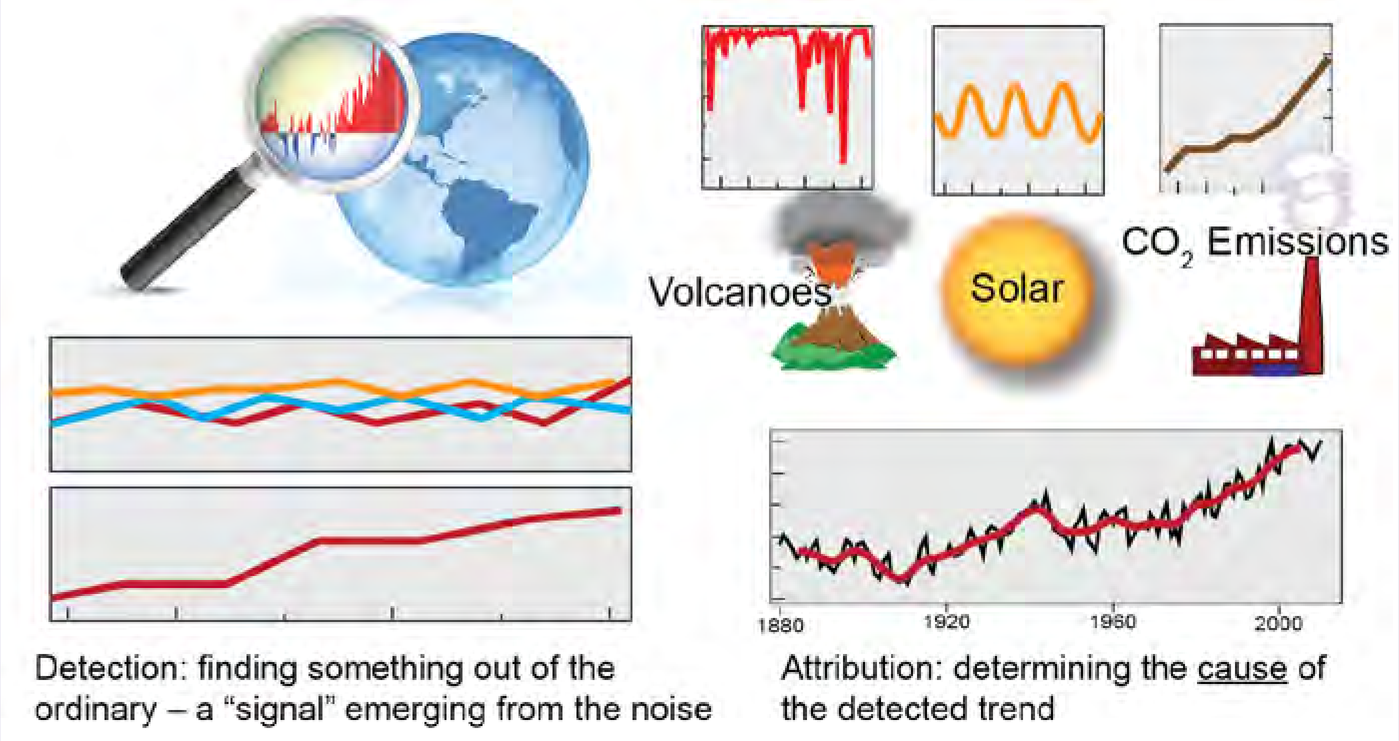


Figure 16. Simplified image of the methodology that goes into detection and attribution of climate changes. The natural factors considered usually include changes in the sun's output and volcanic eruptions, as well as natural modes of variability such as El Niño and La Niña. Human factors include the emissions of heat-trapping gases and particles as well as clearing of forests and other land-use changes. (Figure source: NOAA NCDC / CICS-NC).

Human Influences Apparent in Many Aspects of the Changing Climate

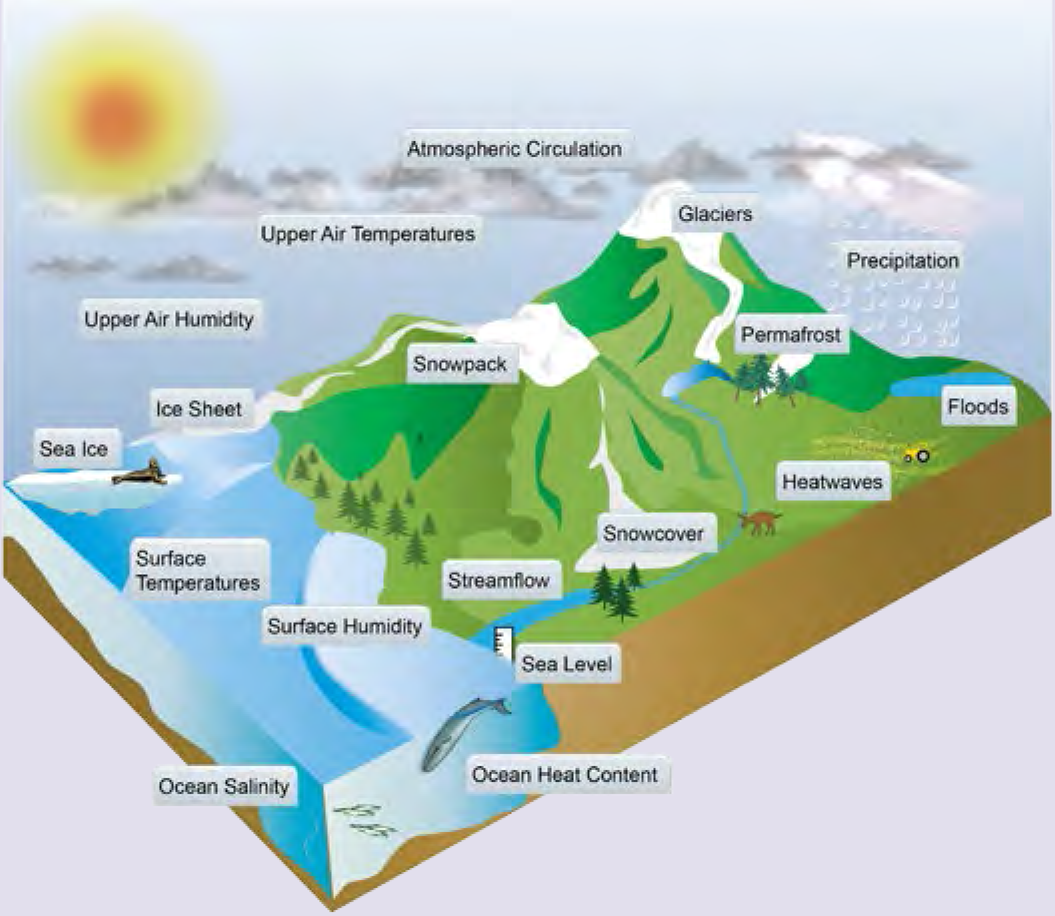


Figure 17. Figure shows examples of the many aspects of the climate system in which changes have been formally attributed to human emissions of heat-trapping gases and particles by studies published in peer-reviewed science literature. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be explained without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the dominant contributor to recently observed climate changes. (Figure source: NOAA NCDC).

effect those factors would have had working together. Then, simulations with no changes in external forcings, only changes due to natural variability, are used to characterize what would be expected from normal internal variations in the climate. The results of these simulations are compared to observations to see which provides the best match for what has really occurred.

Detection and attribution studies have been applied to study a broad range of changes in the climate system as well as a number of specific extreme events that have occurred in recent years. These studies have found that human influences are the only explanation for the observed changes in climate over the last half-century. Such changes include increases in surface temperatures,[46,47] changes in atmospheric vertical temperature profiles,[48] increases in ocean heat content,[49] increasing atmospheric humidity,[50] increases in intensity of precipitation[51] and in runoff,[52] indirectly estimated through changes in ocean salinity,[53] shifts in atmospheric circulation,[54] and changes in a host of other indices.[46] Taken together these paint a coherent picture of a planet whose climate is changing primarily as a result of human activities.

Detection and attribution of specific events is more challenging than for long-term trends as there are less data, or evidence, available from which to draw conclusions. Attribution of extreme events is especially scientifically challenging.[56] Many extreme weather and climate events observed to date are within the range of what could have occurred naturally, but the probability, or odds, of some of these very rare events occurring[57] has been significantly altered by human influences on the climate system. For example, studies have concluded that there is a detectable human influence in recent heat waves in Europe,[58] Russia,[59] and Texas[60] as well as flooding events in England and Wales,[61] the timing and magnitude of snowmelt and resulting streamflow in some western U.S. states,[62,63] and some specific events around the globe during 2011.[64]

Only Human Influence Can Explain Recent Warming

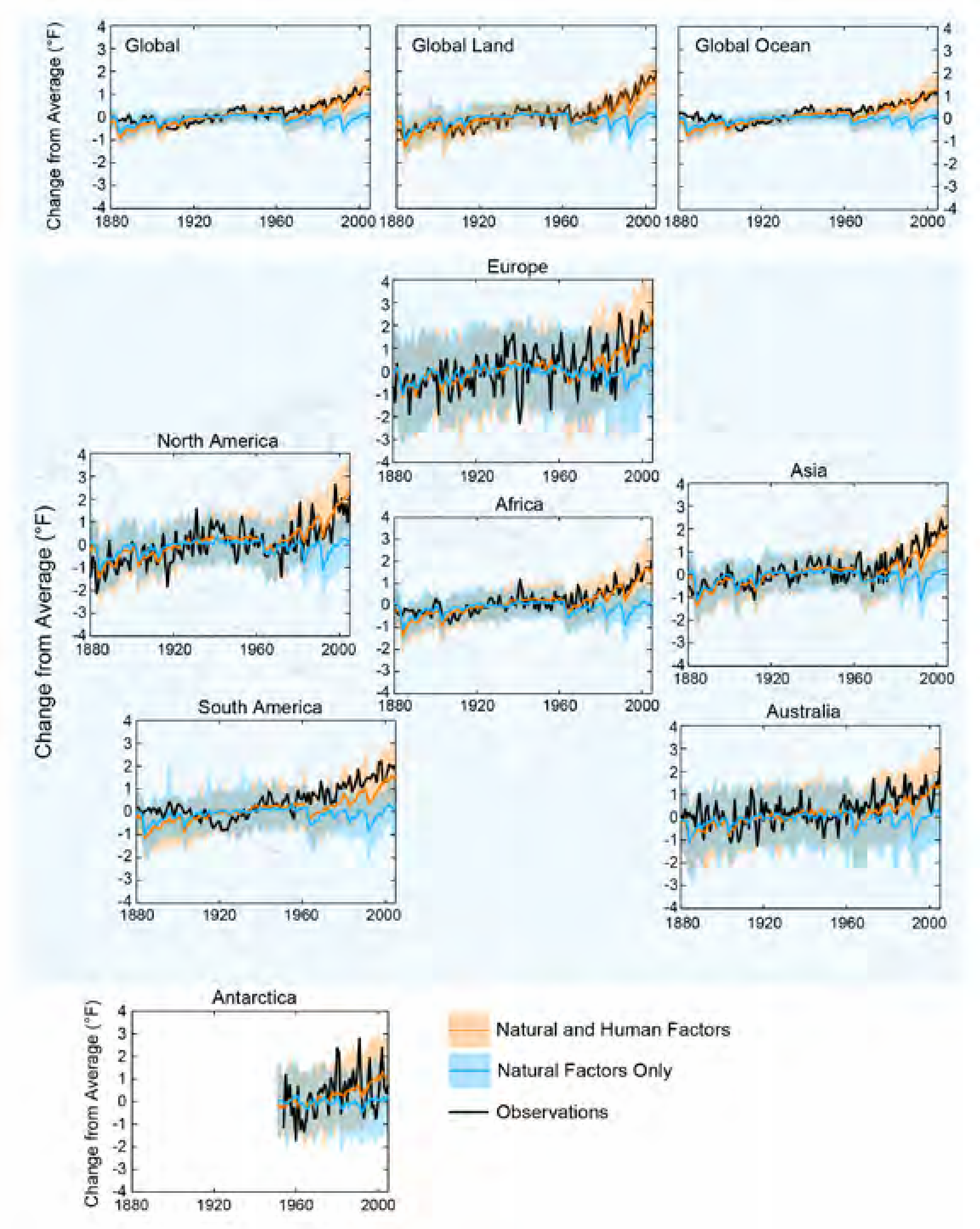


Figure 18. Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the annually averaged observed changes. The blue shading shows climate model simulations that include the effects of natural (solar and volcanic) forcing only. The orange shading shows climate model simulations that include the effects of both natural and human contributions. These analyses demonstrate that the observed changes, both globally and on a continent-by-continent basis, are caused by the influence of human activities on climate. (Figure source: updated from Jones et al. 2013[55]).

Supplemental Message 5.

Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.

A certain amount of climate change is already inevitable due to the build-up of CO_2 in the atmosphere from human activities, most of it since the Industrial Revolution. A decrease in temperature would only be expected if there was an unexpected decrease in natural forcings, such as a reduction in the power of the sun. The Earth's climate system, particularly the ocean, tends to lag behind changes in atmospheric composition by decades, and even centuries, due to the large heat capacity of the oceans and other factors. Even if all emissions of the relevant gases and particles from human activity suddenly stopped, a temperature increase of 0.5°F still would occur over the next few decades,[65] and the human-induced changes in the global carbon cycle would persist for thousands of years.[66]

Global emissions of CO_2 and other heat-trapping gases continue to rise. How much climate will change over this century and beyond depends primarily on: 1) human activities and resulting emissions, and 2) how sensitive the climate is to those changes (that is, the response of global temperature to a change in radiative forcing caused by human emissions). Uncertainties in how the economy will evolve, what types of energy will be used, or what our cities, buildings, or cars will look like in the future all limit scientists' ability to predict the future changes in climate. Scientists can, however, develop scenarios – plausible projections of what might happen, under a given set of assumptions. These scenarios describe possible futures in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

Over the next few decades, the greater part of the range (or uncertainty) in projected global and regional change is the result of natural variability and scientific limitations in our ability to model and understand the Earth's climate system (natural variability is discussed in Supplemental Message 3 and scientific or model uncertainty in Supplemental Message 6). By the second half of the century, however, scenario uncertainty (that is, uncertainty about what will be the level of emissions from human activities) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects.[67] Even though natural variability will continue to occur, most of the difference between present and future climates will be determined by choices that society makes today and over the next few decades. The further out in time we look, the greater the influence of human choices on the magnitude of future change.

For temperature, it is clear that increasing emissions from human activities will drive consistent increases in global and most regional temperatures and that these rising temperatures will increase with the magnitude of future emissions (see Figure 19 and Ch. 2: Our Changing Climate, Figures 2.8 and 2.9). Uncertainty in projected temperature change is generally smaller than uncertainty in projected changes in precipitation or other aspects of climate.

Future climate change also depends on "climate sensitivity," generally summarized as the response of global temperature to a doubling of CO_2 levels in the atmosphere relative to pre-industrial levels of 280 parts per million. If the only impact of increasing atmospheric CO_2 levels were to amplify the natural greenhouse effect (as CO_2 levels increase, more of the Earth's heat is absorbed by the atmosphere before it can escape to space, as discussed in Supplemental Message 1), it would be relatively easy to calculate the change in global temperature that would result from a given increase in CO_2 levels. However, a series of feedbacks within the Earth's climate system acts to amplify or diminish an initial change, adding some uncertainty to the precise climate sensitivity. Some important feedbacks include:

- Clouds – Will warming increase or decrease cloudiness? Will the changes be to lower-altitude clouds that primarily reflect the sun's energy, or higher clouds that trap even more heat within the Earth system?

- Albedo (reflectivity) – How quickly will bright white reflective surfaces, such as snow and ice that reflect most of the sun's energy, melt and be replaced by a dark ocean or land area that absorbs most of the sun's energy? How will vegetation changes caused by climate change alter surface reflectivity?

- Carbon dioxide absorption by the ocean and the biosphere – Will the rate of uptake increase in the future, helping to remove human emissions from the atmosphere? Or will it decrease, causing emissions to build up even faster than they are now?

Feedbacks are particularly important in the Arctic, where rising temperatures melt ice and snow, exposing relatively dark land and ocean, which absorb more of the sun's energy, heating the region even further. Rising temperatures also thaw permafrost, releasing carbon dioxide and methane trapped in the previously frozen ground into the atmosphere, where they further amplify the greenhouse effect (see Supplemental Message 1). Both of these feedbacks act to further amplify the initial warming due to human emissions of carbon dioxide and other heat-trapping gases.

Together, these and other feedbacks determine the long-term response of the Earth's temperature to an increase in carbon dioxide and other emissions from human activities. Past observations, including both recent measurements and studies that look at climate changes in the distant past, cannot tell us precisely how sensitive the climate system will be to increasing emissions of heat-trapping gases if we are starting from today's conditions. They can tell us, however, that the net effect of these feedbacks will be to increase, not diminish, the direct warming effect. In other words, the climate system will warm by more than would be expected from the greenhouse effect alone.

Quantifying the effect of these feedbacks on global and regional climate is the subject of ongoing data collection and active research. As noted above, one measure used to study these effects is the "equilibrium climate sensitivity," which is an estimate of the temperature change that would result, once the climate had reached an equilibrium state, as a result of doubling the CO_2 concentration from pre-industrial levels. The equilibrium climate sensitivity has long been estimated to be in the range of 2.7°F to 8.1°F. The 2007 IPCC Fourth Assessment Report[15] refined this range based on more recent evidence to conclude that the value is likely to be in the range 3.6°F to 8.1°F, with a most probable value of about 5.4°F, based upon multiple observational and modeling constraints, and that it is very unlikely to be less than 2.7°F. Climate sensitivities determined from a variety of evidence agree well with this range, including analyses of past paleoclimate changes.[68,69] This is substantially greater than the increase in temperature from just the direct radiative effects of the CO_2 increase (around 2°F).

Some recent studies (such as Fasullo and Trenberth 2012[70]) have suggested that climate sensitivities are at the higher end of this range, while others have suggested values at the lower end of the range.[71,72] Some recent studies have even suggested that the climate sensitivity may be less than 2.7°F based on analyses of recent temperature trends.[72] However, analyses based on recent temperature trends are subject to significant uncertainties in the treatment of natural variability,[69] the effects of volcanic eruptions,[73] and the effects of recent accelerated penetration of heat to the deep ocean.[74]

The equilibrium climate sensitivity is sometimes confused with the "transient climate response," defined as the temperature change for a 1% per year CO_2 increase, and calculated using the difference between the start of the experiment and a 20-year period centered on the time of CO_2 doubling. This value is generally smaller than the equilibrium climate sensitivity because of the slow rate at which heat transfers between the oceans and the atmosphere due to transient heat uptake of the ocean. The transient climate response is better constrained than the equilibrium climate sensitivity.[15] It is very likely larger than 1.8°F and very unlikely to be greater than 5.4°F. This transient response includes feedbacks that respond to global temperature change over timescales of years to decades. These "fast" feedbacks include increases in atmospheric water vapor, reduction of ice and snow, warming of the ocean surface, and changes in cloud characteristics. The entire response of the climate system will not be fully seen until the deep ocean comes into balance with the atmosphere, a process that can take thousands of years.

Combining the uncertainty due to climate sensitivity with the uncertainty due to human activities produces a range of future temperature changes that overlap over the first half of this century, but begins to separate over the second half of the century as emissions and atmospheric CO_2 levels diverge.

Emissions, Concentrations, and Temperature Projections

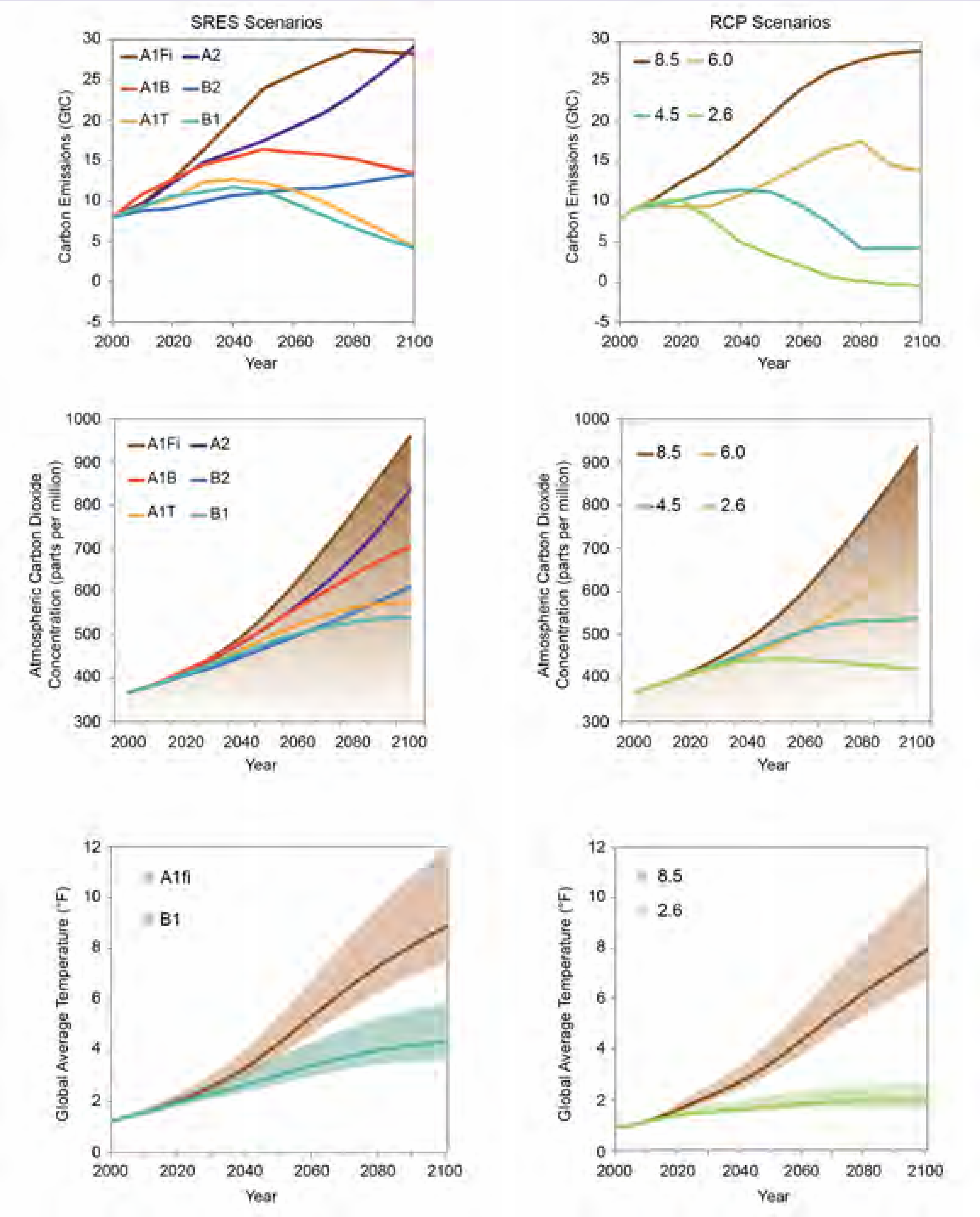


Figure 19. Two families of scenarios are commonly used for future climate projections: the 2000 Special Report on Emission Scenarios (SRES, left) and the 2010 Representative Concentration Pathways (RCP, right). The SRES scenarios are named by family (A1, A2, B1, and B2), where each family is designed around a set of consistent assumptions: for example, a world that is more integrated or more divided. In contrast, the RCP scenarios are simply numbered according to the change in radiative forcing (from +2.6 to +8.5 watts per square meter) that results by 2100. This figure compares SRES and RCP annual carbon emissions (top), carbon dioxide equivalent levels in the atmosphere (middle), and temperature change that would result from the central estimate (lines) and the likely range (shaded areas) of climate sensitivity (bottom). At the top end of the range, the older SRES scenarios are slightly higher. Comparing carbon dioxide concentrations and global temperature change between the SRES and RCP scenarios, SRES A1fI is similar to RCP 8.5; SRES A1B to RCP 6.0 and SRES B1 to RCP 4.5. The RCP 2.6 scenario is much lower than any SRES scenario because it includes the option of using policies to achieve net negative carbon dioxide emissions before end of century, while SRES scenarios do not. (Data from CMIP3 and CMIP5).

Projected Annually-Averaged Temperature ChangeProjections

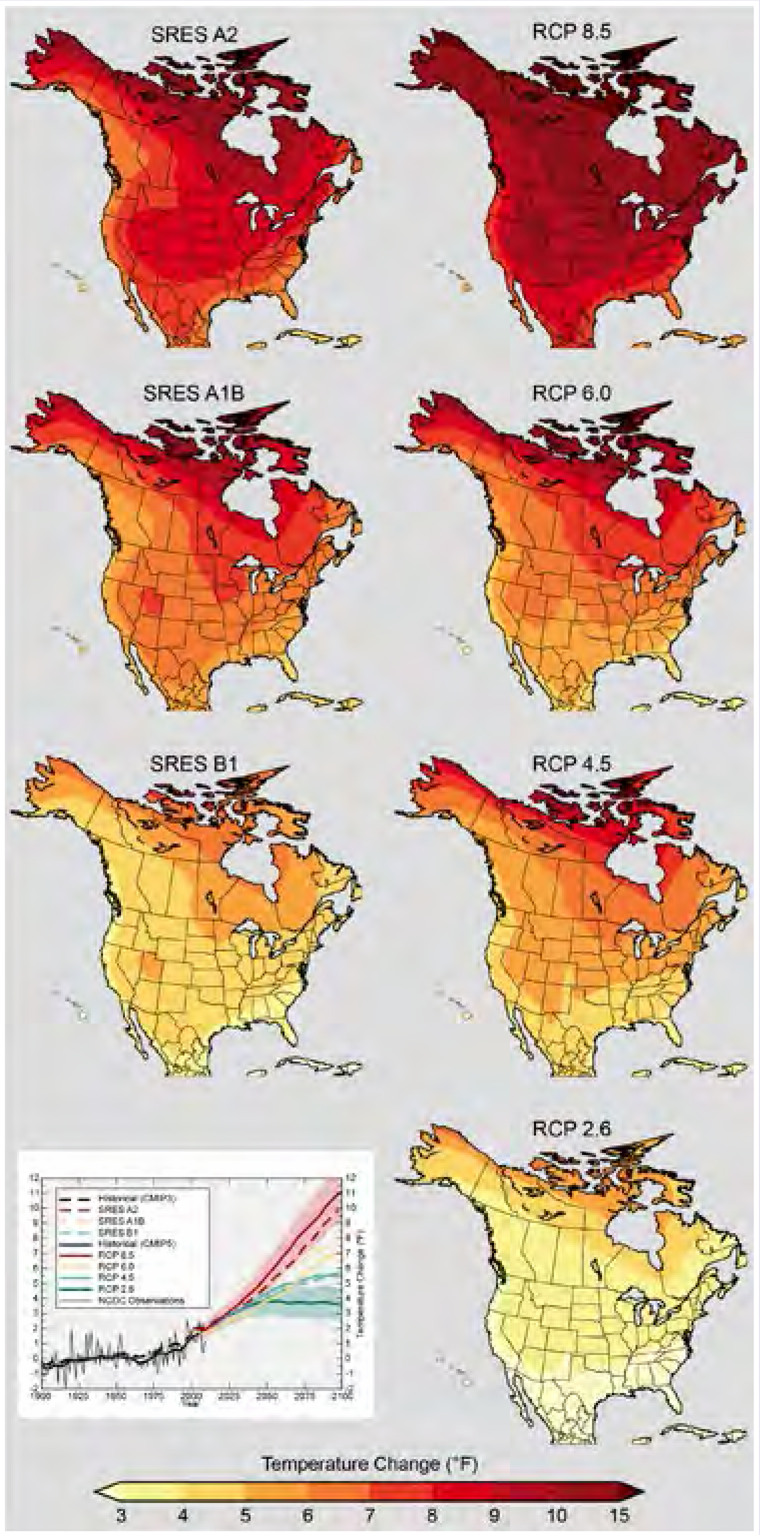


Figure 20. Projected change in surface air temperature at the end of this century (2071-2099) relative to the end of the last century (1970-1999). The older generation of models (CMIP3) and SRES emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. The scenarios are described under Supplemental Message 5 and in Figure 19. Differences between the old and new projections are mostly a result of the differences in the scenarios of the emission of heat-trapping gases rather than the increased complexity of the new models. None of the new scenarios are exactly the same as the old ones, although at the end of the century SRES B1 and RCP 4.5 are roughly comparable, as are SRES A1B and RCP 6.0. (Figure source: NOAA NCDC / CICS-NC).

Projected Wintertime Precipitation Changes

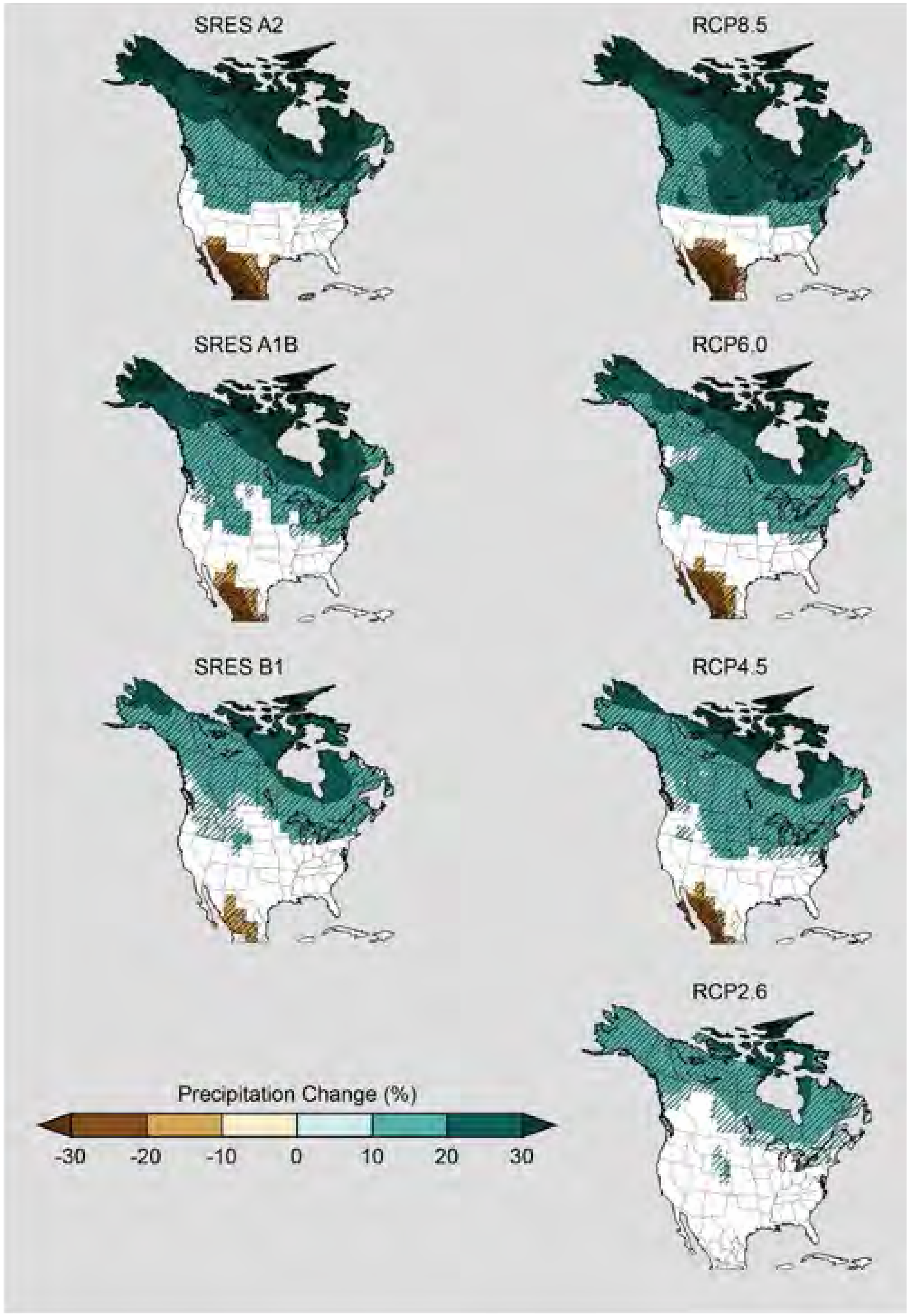


Figure 21. Projected changes in wintertime precipitation at the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In both sets of projections, the northern parts of the U.S. (and Alaska) become wetter. Increases in both the amount of precipitation change and the confidence in the projections go up as the projected temperature rises. In the farthest northern parts of the U.S., much of the additional winter precipitation will still fall as snow. This is not likely to be the case farther south. (Figure source: NOAA NCDC / CICS-NC).

Projected Summertime Precipitation Changes

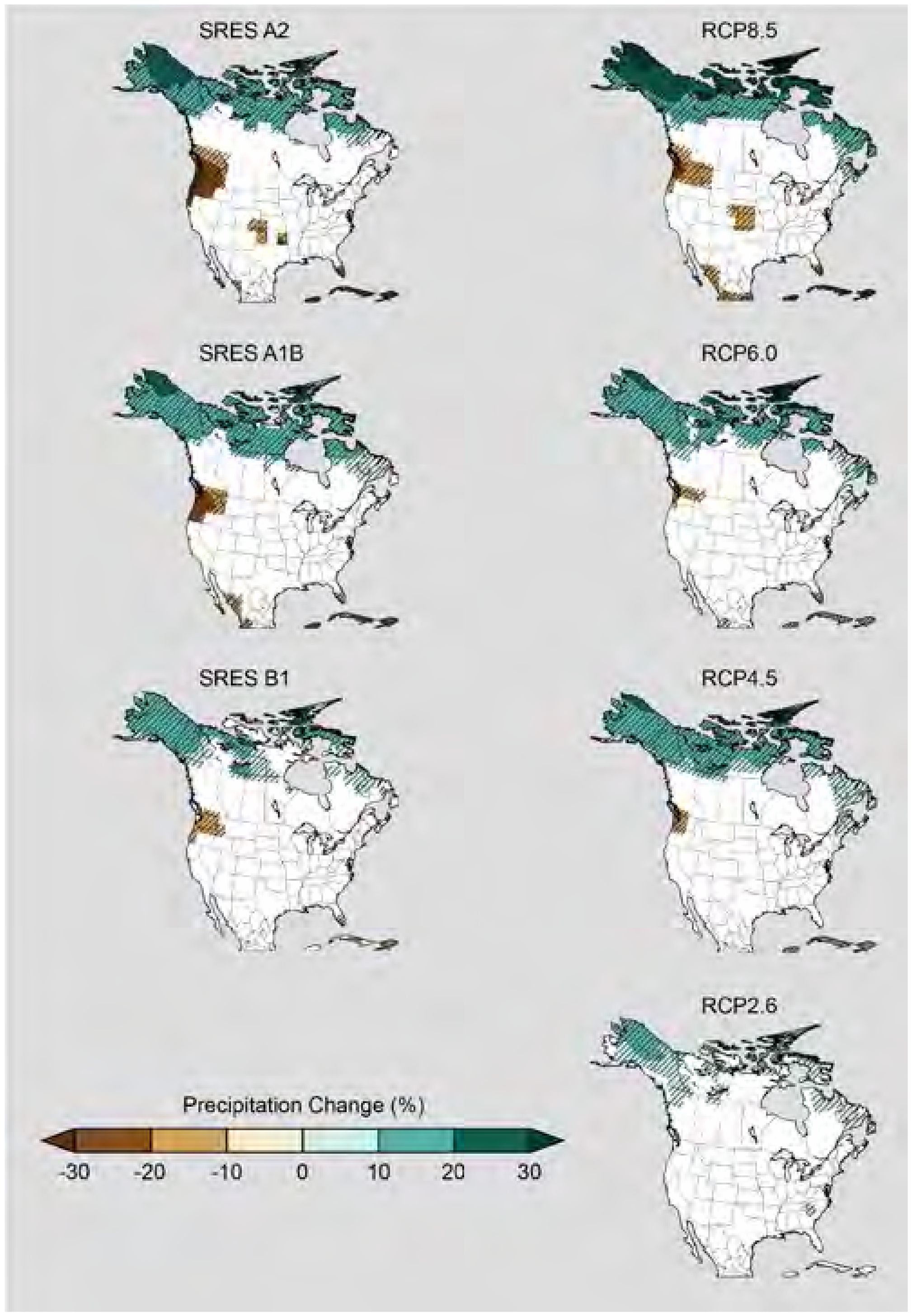


Figure 22. Projected changes in summertime precipitation toward the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate confidence that the changes are not projected to be larger than could be expected from natural variability. In most of the contiguous U.S., decreases in summer precipitation are projected, but not with as much confidence as the winter increases. When interpreting maps of temperature and precipitation projections, readers are advised to pay less attention to small details and greater attention to the large-scale patterns of change. (Figure source: NOAA NCDC / CICS-NC).

Carbon Emissions: Historical and Projected

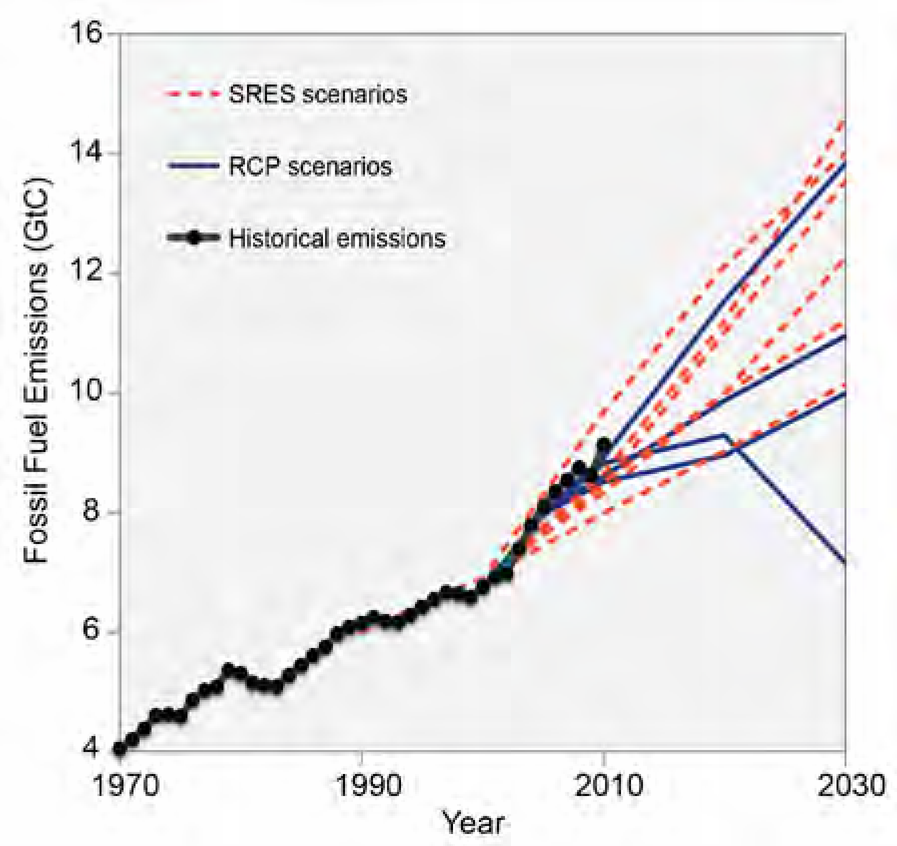


Figure 23. Historical emissions of carbon from fossil fuel (coal, oil, and gas) combustion and land-use change (such as deforestation) have increased over time. The growth rate was nearly three times greater during the 2000s as compared to the 1990s. This figure compares the observed historical (black dots) and projected future SRES (orange dashed lines) and RCP (blue solid lines) carbon emissions from 1970 to 2030. (Data from Boden et al. 2011[75] plus preliminary values for 2009 and 2010 based on BP statistics and U.S. Geological Survey cement data).

Supplemental Message 6.

Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.

Climate scientists use a wide range of observational and computational tools to understand the complexity of the Earth's climate system and to study how that system responds to external forces, including the effect of humans on climate. Observational tools are described in Supplemental Message 2.

Computational tools include models that simulate different parts of the climate system. The most sophisticated computational tools used by climate scientists are **global climate models** (previously referred to as "general circulation models"), or GCMs. Global climate models are mathematical models that simulate the physics, chemistry, and, increasingly, the biology that influence the climate system. GCMs are built on fundamental equations of physics that include the conservation of energy, mass, and momentum, and how these are exchanged among different parts of the climate system. Using these fundamental relationships, the models generate many important features that are evident in the Earth's climate system: the jet stream that circles the globe 30,000 feet above the Earth's surface; the Gulf Stream and other ocean currents that transport heat from the tropics to the poles; and even, when the models can be run at a fine enough spatial resolution to capture these features, hurricanes in the Atlantic and typhoons in the Pacific.

GCMs and other physical models are subject to two main types of uncertainty. First, because scientific understanding of the climate system is not complete, a model may not include an important process. This could be because that process is not yet recognized, or because it is known but is not yet understood well enough to be modeled accurately. For example, the models do not currently include adequate treatments of dynamical mechanisms that are important to melting ice sheets. The existence of these mechanisms is known, but they are not yet well enough understood to simulate accurately at the global scale. Also, observations of climate change in the distant past suggest there might be "tipping points," or mechanisms of abrupt changes in climate change, such as shifts in ocean circulation, that are not adequately understood.[76] These are discussed further in Appendix 4: FAQ T.

Second, many processes occur at finer temporal and spatial (time and space) scales than models can resolve. Models instead must approximate what these processes would look like at the spatial scale that the model can resolve using empirical equations, or parameterizations, based on a combination of observations and scientific understanding. Examples of important processes that must be parameterized in climate models include turbulent mixing, radiational heating/cooling, and small-scale physical processes such as cloud formation and precipitation, chemical reactions, and exchanges between the biosphere and atmosphere. For example, these models cannot represent every raindrop. However, they can simulate the total amount of rain that would fall over a large area the size of a grid cell in the model. These approximations are usually derived from a limited set of observations and/or higher resolution modeling and may not hold true for every location or under all possible conditions.

GCMs are constantly being enhanced as scientific understanding of climate improves and as computational power increases. For example, in 1990, the average model divided up the world into grid cells measuring more than 300 miles per side. Today, most models divide the world up into grid cells of about 60 to 100 miles per side, and some of the most recent models are able to run short simulations with grid cells of only 15 miles per side. Supercomputer capabilities are the primary limitation on grid cell size. Newer models also incorporate more of the physical processes and components that make up the Earth's climate system. The very first global climate models were designed to simulate only the circulation of the atmosphere. Over time, the ocean, clouds, land surface, ice, snow, and other features were added one by one. Most of these features were new modules that were developed by experts in those fields and then added into an existing GCM framework. Today, there are more than 35 GCMs created and maintained by more than 20 modeling groups around the world. Some of the newest models are known as Earth System Models, or ESMs, which include all the previous components of a typical GCM but also incorporate modules that represent additional aspects of the climate system, including agriculture, vegetation, and the carbon cycle.

Some models are more successful than others at reproducing observed climate and trends over the past century,[77] or the large-scale dynamical features responsible for creating the average climate conditions over a certain region (such as the Arctic[78] or the Caribbean[79]). Evaluation of models' success often depends on the variable or metric being considered in the analysis, with some models performing better than others for certain regions or variables.[80] However, all future simulations agree that both global and regional temperatures will increase over this century in response to increasing emissions of heat-trapping gases from human activities.[15]

Differences among model simulations over several years to several decades arise from natural variability (as discussed in Supplemental Message 3) as well as from different ways models characterize various small-scale processes. Averaging simulations from multiple models removes the effects of randomly occurring natural variations. The timing of natural variations is largely unpredictable beyond several seasons (although such predictability is an active research area). For this reason, model simulations are generally averaged (as the last stage in any analysis) to make it easier to discern the impact of external forcing (both human and natural). The effect of averaging on the systematic errors depends on the extent to which models have similar errors or offsetting errors.

Despite their increasing resolution, most GCMs cannot simulate fine-scale changes at the regional to local scale. For that reason, **downscaling** is often used to translate GCM projections into the high-resolution information required as input to impact analyses. There are two types of models commonly used for downscaling: dynamical and statistical.

Dynamical downscaling models are often referred to as regional climate models since they include many of the same physical processes that make up a global climate model, but simulate these processes at higher resolution and over a relatively small area, such as the Northwest or Southeast United States. At their boundaries, regional climate models use output from GCMs to simulate what is going on in the rest of the world. Regional climate models are computationally intensive, but provide a broad range of output variables including atmospheric circulation, winds, cloudiness, and humidity at spatial scales ranging from about 6 to 30 miles per grid cell. They are also subject to the same types of uncertainty as a global model, such as not fully resolving physical processes that occur at even smaller scales. Regional climate models have additional uncertainty related to how often their boundary conditions are updated and where they are defined. These uncertainties can have a large impact on the precipitation simulated by the models at the local to regional scale. Currently, a limited set of regional climate model simulations based on one future scenario and output from five CMIP3 GCMs is available from the North American Regional Climate Change Assessment Program (these are the "NARCCAP" models used in some sections of this report). These simulations are useful for examining certain impacts over North America. However, they do not encompass the full range of uncertainty in future projections due to both human activities and climate sensitivity described in Supplemental Message 5.

Statistical downscaling models use observed relationships between large-scale weather features and local climate to translate future projections down to the scale of observations. Statistical models are generally very effective at removing errors in historical simulated values, leading to a good match between the average (multi-decadal) statistics of observed and statistically downscaled climate at the spatial scale and over the historical period of the observational data used to train the statistical model. However, statistical models are based on the key assumption that the relationship between large-scale weather systems and local climate will remain constant over time. This assumption may be valid for lesser amounts of change, but could lead to errors, particularly in precipitation extremes, with larger amounts of climate change.[81] Statistical models are generally flexible and less computationally demanding than regional climate models. A number of databases provide statistically downscaled projections for a continuous period from 1960 to 2100 using many global models and a range of higher and lower future scenarios (for example, the U.S. Geological Survey database described by Maurer et al. 2007[82]).[83,84] Statistical downscaling models are best suited for analyses that require a range of future projections that reflect the uncertainty in emissions scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes.

Ideally, climate impact studies could use both statistical and dynamical downscaling methods. Regional climate models can directly simulate the response of regional climate processes to global change, while statistical models can better remove any biases in simulations relative to observations. However, rarely (if ever) are the resources available to take this approach. Instead, most assessments tend to rely on one or the other type of downscaling, where the choice is based on the needs of the assessment. If the study is more of a sensitivity analysis, where using one or two future simulations is not a limitation, or if it requires many climate variables as input, then regional climate modeling may be more appropriate. If the study needs to resolve the full range of projected changes under multiple models and scenarios or is more constrained by practical resources, then statistical downscaling may be more appropriate. However, even within statistical downscaling, selecting an appropriate method for any given study depends on the questions being asked. The variety of techniques ranges from a simple "delta" (change or difference) approach (subtracting historical simulated values from future values, and adding the resulting delta to historical observations, as used in the first national climate assessment[85]) to complex clustering and neural network techniques that rival dynamical downscaling in their demand for computational resources and high-frequency model output (for example, Kostopoulou and Jones 2007[86]; Vrac et al. 2007[81]). The delta approach is adequate for studies that are only interested in changes in seasonal or annual average temperature. More complex methods must be used for studies that require information on how climate change may affect the frequency or timing of precipitation and climate extremes.

Modeling the Climate System

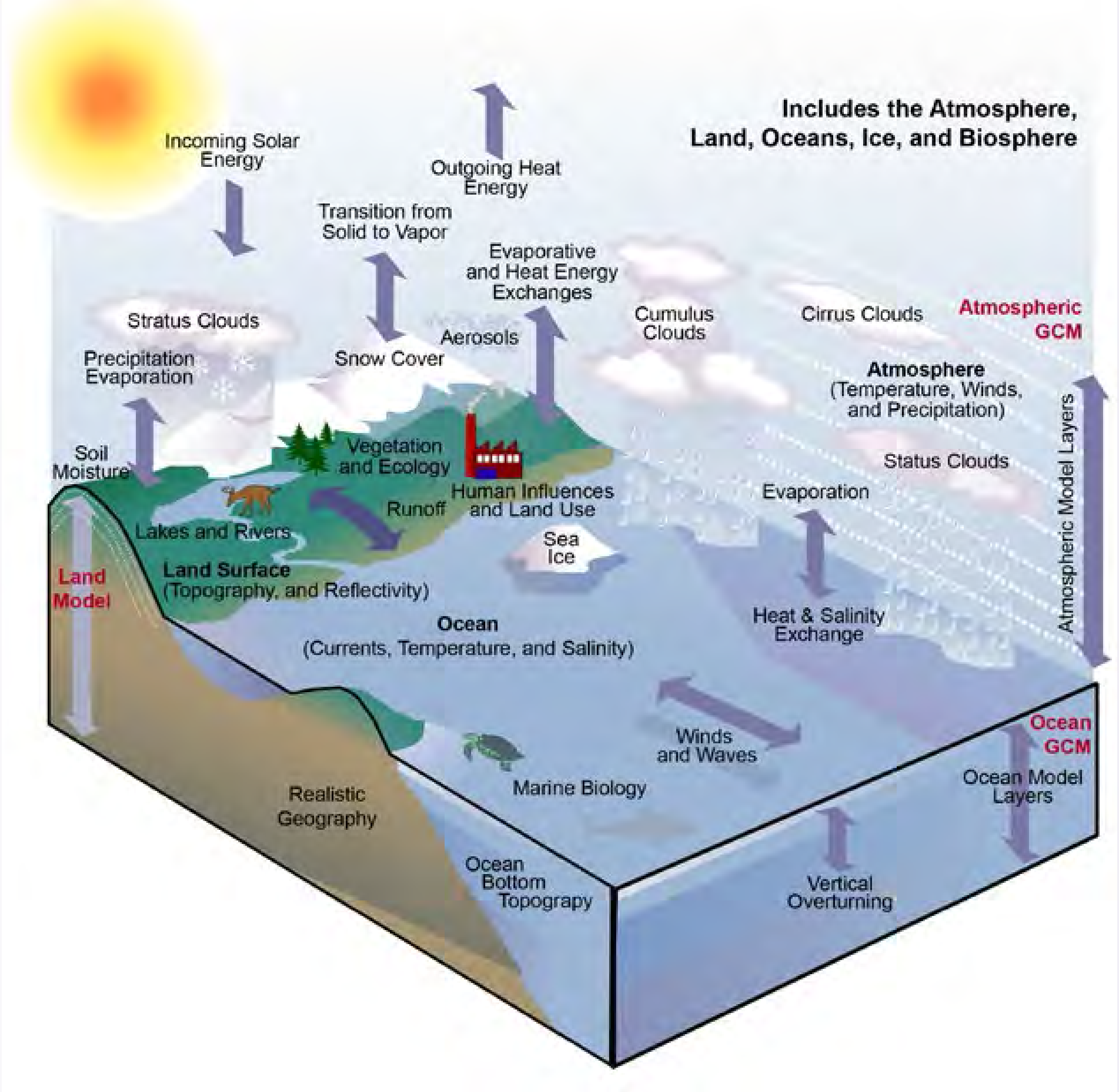


Figure 24. Some of the many processes often included in models of the Earth's climate system. (Figure source: Karl and Trenberth 2003[87]).

Increasing Model Resolution

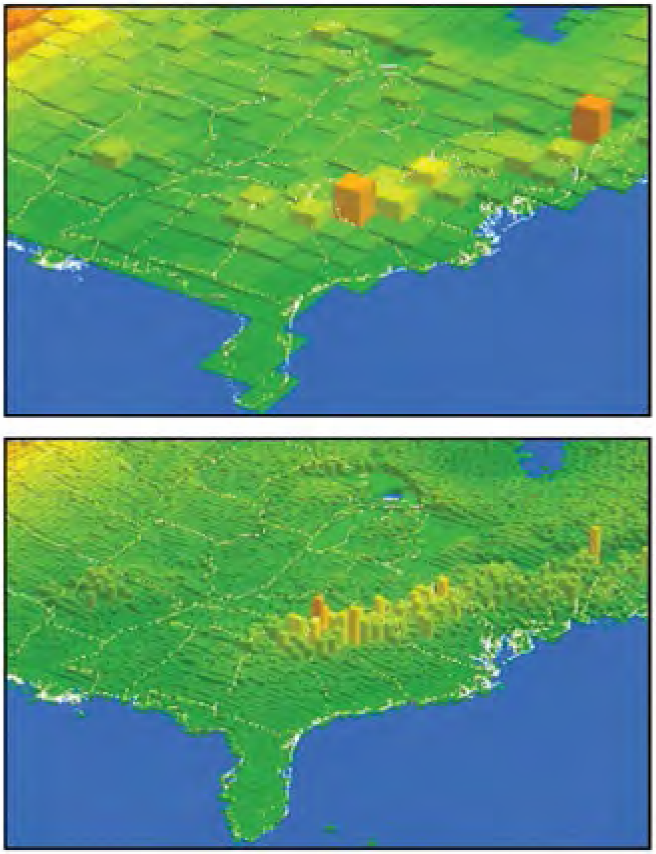
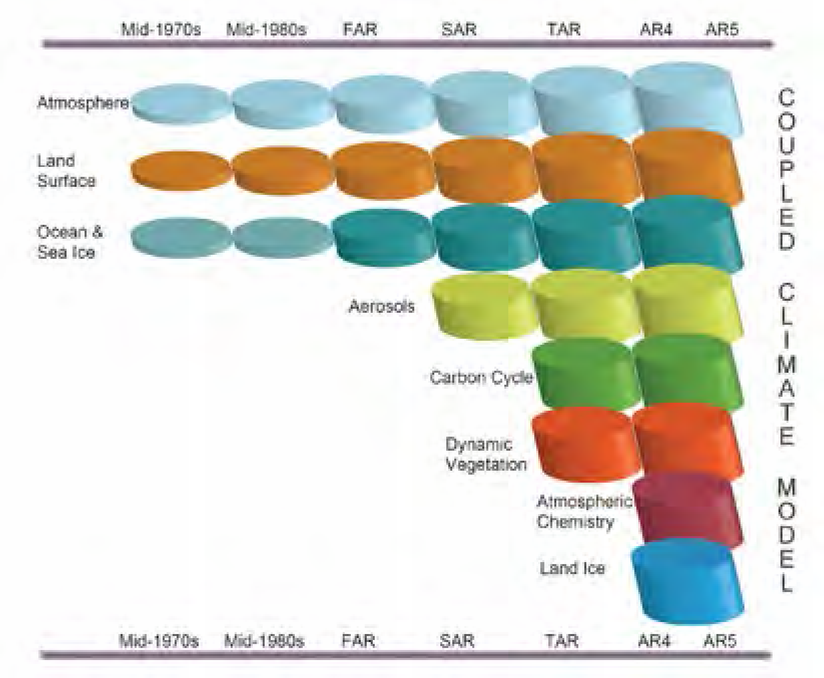


Figure 25. Top: Illustration of the eastern North American topography in a resolution of 68 x 68 miles (110 x 110 km). Bottom: Illustration of the eastern North American topography in a resolution of 19 x 19 miles (30 x 30 km).

Increasing Climate Model Components



Intergovernmental Panel on Climate Change Reports	
FAR	1990
SAR	1995
TAR	2001
AR4	2007
AR5	2013

Figure 26. The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (for example, the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably. (Figure source: adapted from Cubasch et al. 2013[88]).

Supplemental Message 7.

Scientific understanding of observed temperature changes in the United States has greatly improved, confirming that the U.S. is warming due to heat-trapping gas emissions, consistent with the climate change observed globally.

There have been substantial recent advances in our understanding of the continental U.S. temperature records. Numerous studies have looked at many different aspects of the record.[28,89,90,91,92,93] These studies have increased confidence that the U.S. is warming, and refined estimates of how much.

Historical temperature data are available for thousands of weather stations. However, for a variety of practical and often unavoidable reasons, there have been frequent changes to individual stations and to the network as a whole. Two changes are particularly important. The first is a widespread change in the time at which observers read their thermometers. Second, most stations now use electronic instruments rather than traditional glass thermometers.

Extensive work has been done to document the effect of these changes on historical temperatures. For example, the change from afternoon to morning observations resulted in systematically lower temperatures for both maximum and minimum, artificially cooling the U.S. temperature record by about 0.5°F.[93,94] The change in instrumentation was equally important but more complex. New electronic instruments generally recorded higher minimum temperatures, yielding an artificial warming of about 0.25°F, and lower maximum temperatures, resulting in an artificial cooling of about 0.5°F. This has been confirmed by extended period side-by-side instrument comparisons.[95] Confounding this, as noted by a recent citizen science effort, the new instruments were often placed nearer buildings or other man-made structures.[96] Analyses of the changes in siting indicate that this had a much smaller effect than the change in instrumentation across the network as a whole.[89,91,93]

Extensive work has been done to develop statistical adjustments that carefully remove these and other non-climate elements that affect the data. To confirm the efficacy of the adjustments, several sensitivity assessments have been undertaken. These include:

- a comparison with the U.S. Climate Reference Network;[91,97]
- analyses to evaluate biases and uncertainties;[93]
- comparisons to a range of state-of-the-art meteorological data analyses;[92] and
- in-depth analyses of the potential impacts of urbanization.[90]

These assessments agree that the corrected data do not overestimate the rate of warming. Rather, because the average effect of these issues was to reduce recorded temperatures, adjusting for these issues tends to reveal a larger long-term warming trend. The impact is much larger for maximum temperature as compared to minimum temperature because the adjustments account for two distinct artificial cooling signals: the change in observation time and the change in instrumentation. The impact is smaller for minimum temperature because the artificial signals roughly offset one another (the change in observation time cooling the record, the change in instrumentation warming the record). Even without these adjustments, however, both maximum and minimum temperature records show increases over the past century.

Geographically, maximum temperature has increased in most areas except in parts of the western Midwest, northeastern Great Plains, and the Southeast regions. Minimum temperature exhibits the same pattern of change with a slightly greater area of increases. The causes of these slight differences between maximum and minimum temperature are a subject of ongoing research.[98] In general, the uncorrected data exhibit more extreme trends as well as larger spatial variability; in other words, the adjustments have a smoothing effect.

The corrected temperature record also confirms that U.S. average temperature is increasing in all four seasons. The heat that occurred during the Dust Bowl era is prominent in the summer record. The warmest summer on record was 1936, closely followed by 2011. However, twelve of the last fourteen summers have been above average. Temperatures during the other seasons have also generally been above average in recent years.

Trends in Maximum and Minimum Temperatures

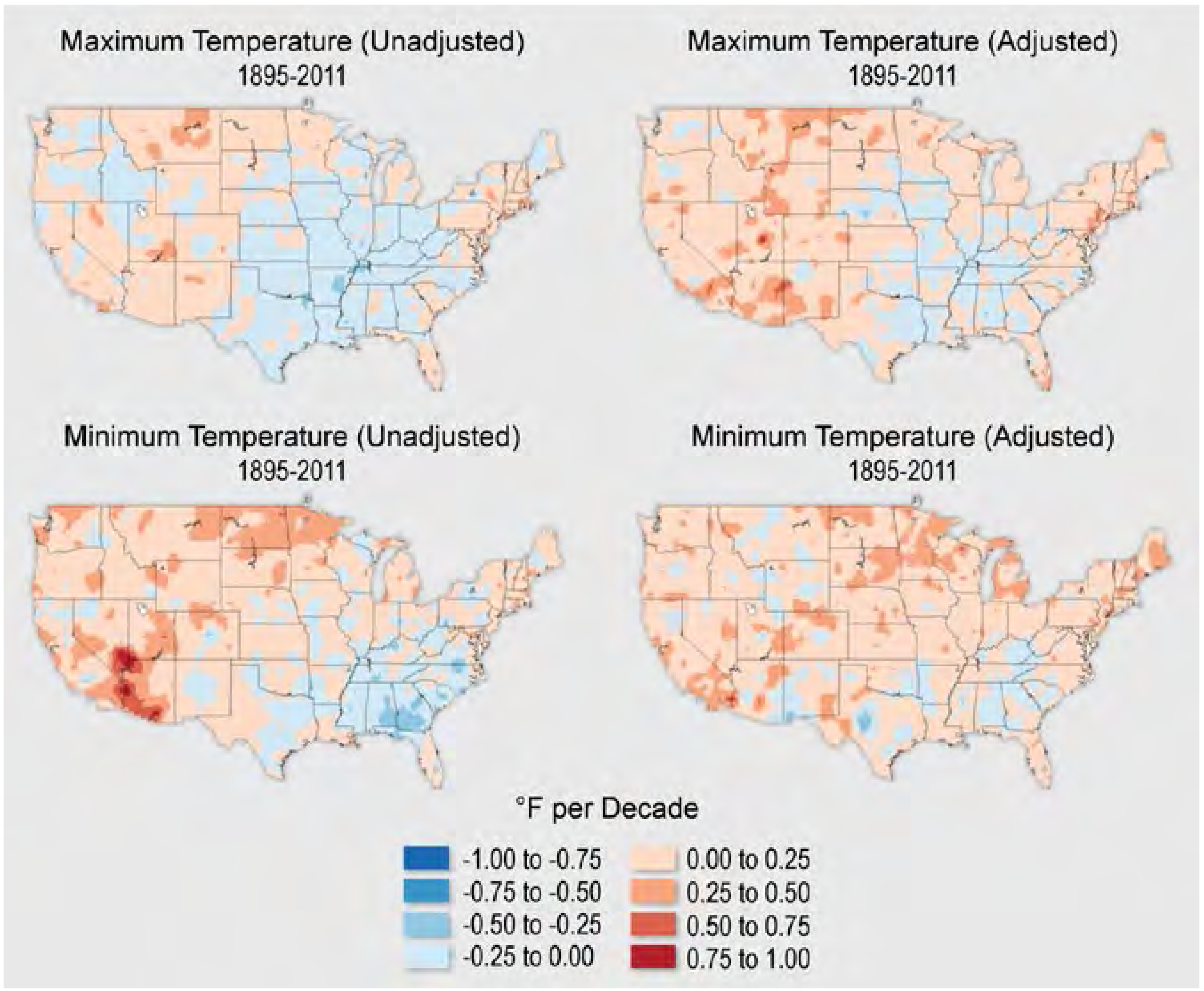


Figure 27. Geographic distribution of linear trends in the U.S. Historical Climatology Network for the period 1895-2011. (Figure source: updated from Menne et al. 2009[91]).

U.S. Seasonal Temperatures

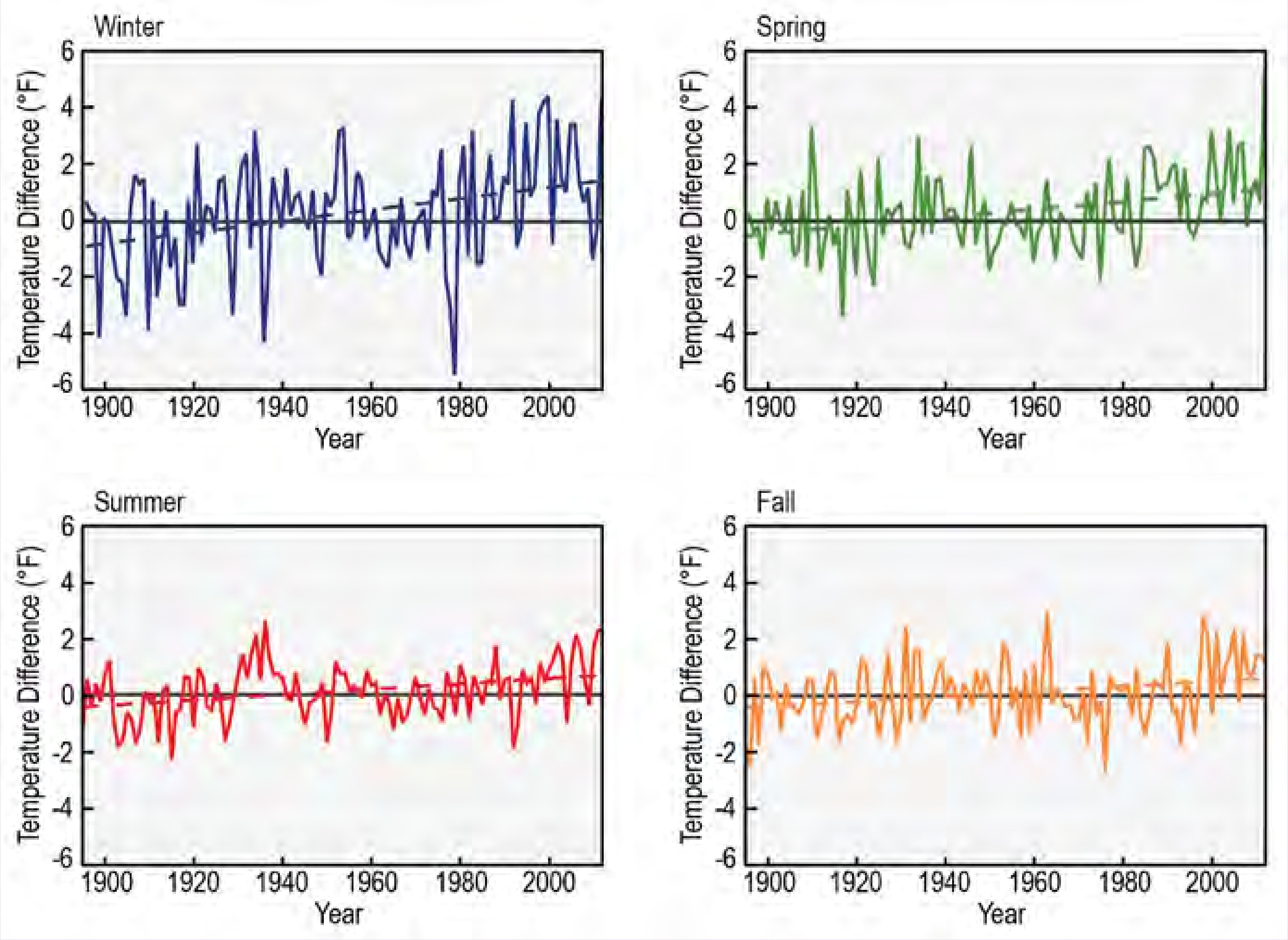


Figure 28. Continental U.S. seasonal temperatures (relative to the 1901-1960 average) for winter, spring, summer, and fall all show evidence of increasing trends. Dashed lines show the linear trends. Stronger trends are seen in winter and spring as compared to summer and fall. (Figure source: updated from Kunkel et al. 2013[99]).

Supplemental Message 8.

Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.

While surface air temperature is the most widely cited measure of climate change, other aspects of climate that are affected by temperature are often more directly relevant to both human society and the natural environment. Examples include shorter duration of ice on lakes and rivers, reduced glacier extent, earlier melting of snowpack, reduced lake levels due to increased evaporation, lengthening of the growing season, and changes in plant hardiness zones. Changes in these and many other variables are consistent with the recent warming over much of the United States. Taken as a whole, these changes provide compelling evidence that increasing temperatures are affecting both ecosystems and human society.

Striking decreases in the coverage of ice on the Great Lakes have occurred over the last few decades (see Ch 2: Our Changing Climate, Key Message 11). The annual average ice cover area for the Great Lakes, which typically shows large year-to-year variability, has sharply declined over the last 30+ years.[100] Based on records covering the winters of 1972-1973 through 2010-2011, 12 of the 19 winters prior to 1991-1992 had annual average ice cover greater than 20% of the total lake area while 15 of the 20 winters since 1991-1992 have had less than 20% of the total lake area covered with ice. This includes the three lowest ice extent winters of 1997-1998, 2001-2002, and 2005-2006. A reduction in ice leading to more open water in winter raises concerns about possible increases in lake effect snowfall, although future trends will also depend on the difference between local air and water temperatures.

Smaller lakes in other parts of the country show similar changes. For example, the total duration of ice cover on Lake Mendota in Madison, Wisconsin, has decreased from about 120 days in the late 1800s to less than 100 days in most years since 1990.[101] Average dates of spring ice disappearance on Minnesota lakes show a trend toward earlier melting over the past 60 years or so. These changes affect the recreational and commercial activities of the surrounding communities.

A long-term record of the ice-in date (the first date in winter when ice coverage closes the lake to navigation) on Lake Champlain in Vermont shows that the lake now freezes approximately two weeks later than in the early 1800s and over a week later than 100 years ago.[102] Later ice-in dates are an indication of higher lake temperatures, as it takes longer for the warmer water to freeze in winter. Prior to 1950, the absence of winter ice cover on Lake Champlain was rare, occurring just three times in the 1800s and four times between 1900 and 1950. By contrast, it remained ice-free during 42% of the winters between 1951 and 1990, and since 1991, Lake Champlain has remained ice-free during 64% of the winters. One- to two-week advances of ice breakup dates and similar length delays of freeze-up dates are also typical of lakes and rivers in Canada, Scandinavia, and northern Asia.[15]

While shorter durations of lake ice enhance navigational opportunities during winter, decreasing water levels in the Great Lakes present risks to navigation, especially during the summer. Water levels on Lakes Superior, Michigan, and Ontario have been below their long-term (1918-2008) averages for much of the past decade.[103] The summer drought of 2012 left Lakes Michigan and Ontario approximately one foot below their long-term averages. As noted in the second national climate assessment,[1] projected water level reductions for this century in the Great Lakes range from less than a foot under lower emissions scenarios to between 1 and 2 feet under high-

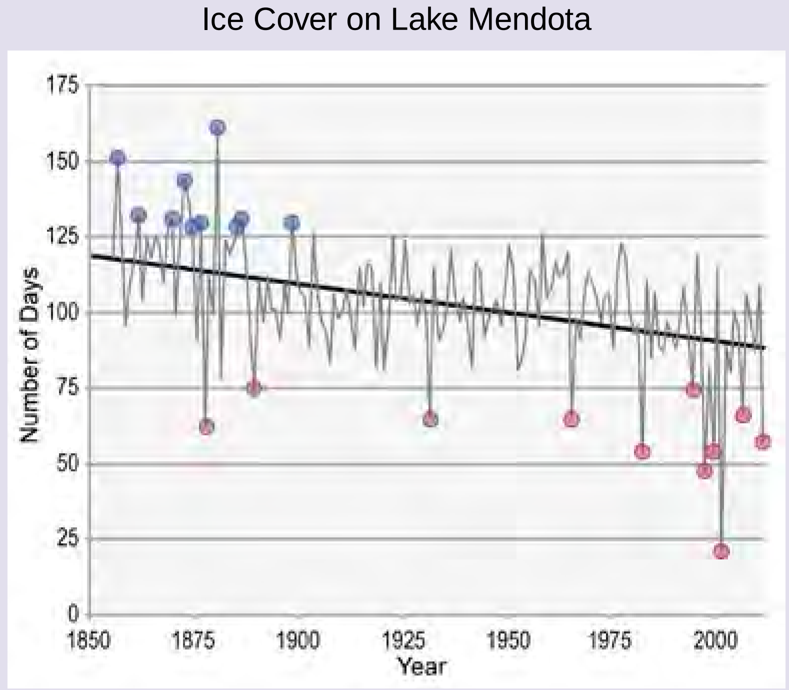
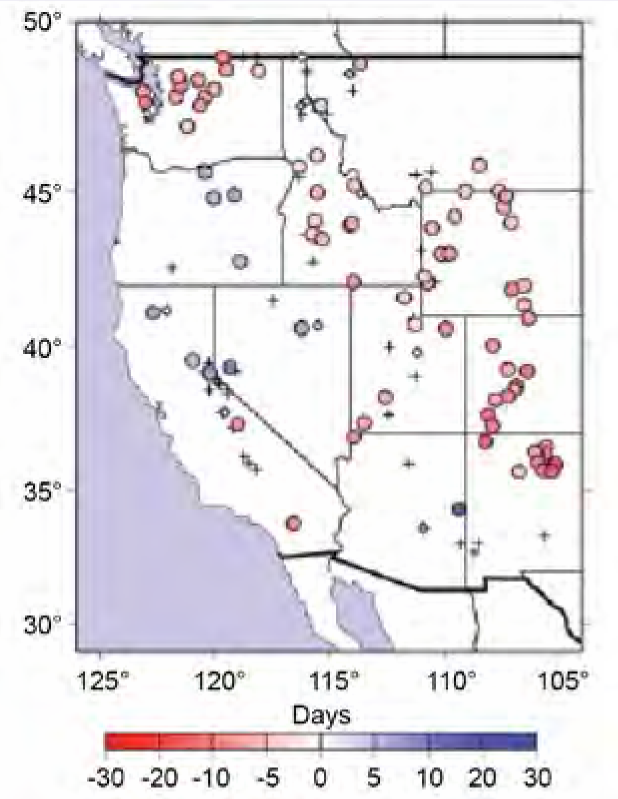


Figure 29. The duration, or number of days, of ice cover on Lake Mendota, Wisconsin, has decreased over time. The 10 longest ice seasons are marked by blue circles, and the 11 shortest ice seasons are marked by red circles. Seven of the 10 shortest ice cover seasons have occurred since 1980. (Figure source: Kunkel et al. 2013[107]).



Streamflow from Snowmelt Coming Earlier in the Year

Figure 30. At many locations in the western U.S., the timing of streamflow in rivers fed by snowpack is shifting to earlier in the year. Red dots indicate stream gauge locations where half of the annual flow is now arriving anywhere from 5 to 20 days earlier each year for 2001-2010, relative to the 1951-2000 average. Blue dots indicate locations where the annual flow is now arriving later. Crosses indicate locations where observed changes are not statistically different from the past century baseline at 90% confidence levels, diamonds indicate gauges where the timing difference was significantly different at 90% confidence, and dots indicate gauges where timing was different at 95% confidence level. (Updated from Stewart et al. 2005[110]).

er emissions scenarios, with the smallest changes projected for Lake Superior and the largest change projected for Lakes Michigan and Huron.[83] A notable feature is the large range (several feet) of water level projections among models.[104] More recent studies have indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[105] Accounting for land-atmosphere feedbacks may further reduce the estimates of lake level declines.[106] These recent studies, along with the large spread in models, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty.

In the U.S. Southwest, indications of a changing climate over the last five decades include decreases in mountain snowpack,[108] earlier dates of snowmelt runoff,[109,110] earlier onset of spring (as indicated by shifts in the timing of plant blooms and spring snowmelt-runoff pulses),[111] general shifts in western hydroclimatic seasons,[112] and trends toward more precipitation falling as rain instead of snow over the West.[113] The ratio of precipitation falling as rain rather than snow, the amount of water in snowpack, and the timing of peak stream flow on snowmelt-fed rivers all changed as expected with warming over the past dozen years, relative to the last century baselines.[62]

Changing temperatures affect vegetation through lengthening of the frost-free season and the corresponding growing season, and changing locations of plant tolerance thresholds. The U.S. average frost-free season length (defined as the number of days between the last and first occurrences of 32°F in spring and autumn, respectively) increased by about two weeks during the last century.[114] The increase was much greater in the western than in the eastern United States. Consistent with the recent observed trends in frost-free season length, the largest projected changes in growing season length are in the mountainous regions of the western United States, while smaller changes are projected for the Midwest, Northeast, and Southeast. Related plant and animal changes include a northward shift in the typical locations of bird species[115] and a shift since the 1980s toward earlier first-leaf dates for lilac and honeysuckle.[116]

Plant hardiness zones are determined primarily by the extremes of winter cold.[117] Maps of plant hardiness have guided the selection of plants for both ornamental and agricultural purposes, and these zones are changing as climate warms. Plant hardiness zones for the U.S. have recently been updated using the new climate normals (1981-2010), and these zones show a northward shift by up to 100 miles relative to the zones based on the older (1971-2000) normals. Even greater northward shifts, as much as 200 miles, are projected over the next 30 years as warming increases. Projected shifts are largest in the major agricultural regions of the central United States.

Evidence of a warming climate across the U.S. is based on a host of indicators: hydrology, ecology, and physical climate. Most of these are changing in ways consistent with increasing temperatures, and are expected to continue to change in the future as a result of ongoing increases in human-induced heat-trapping gas emissions.

Shifts in Plant Hardiness Zones

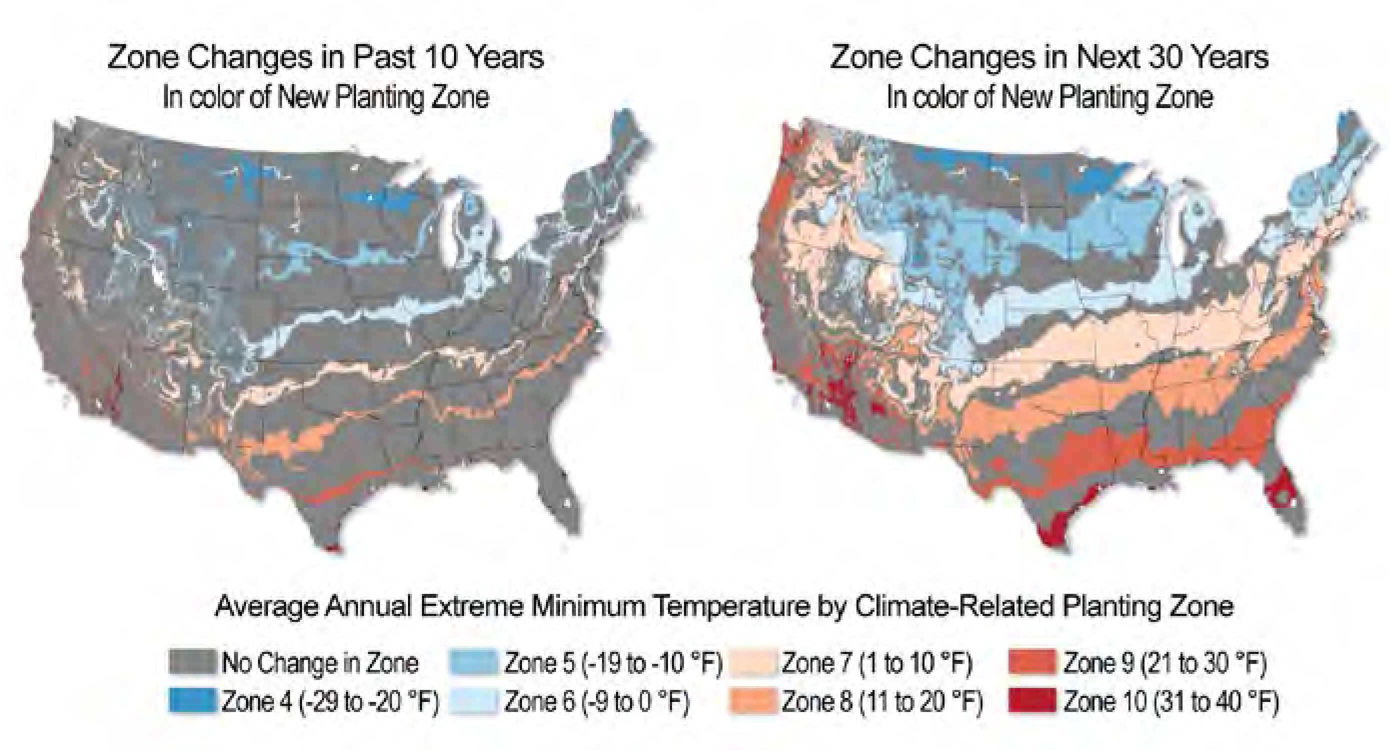


Figure 31. The map on the left shows the change in Plant Hardiness Zones calculated from those based on the 1971-2000 climate to those based on the 1981-2010 climate. Even greater changes are projected over the next 30 years (right). (Figure source: NOAA).

Supplemental Message 9.

Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate change's effects on other types of extreme events continues.

High impact, large-scale extreme events are complex phenomena involving various factors that can vcreate a "perfect storm." Such extreme weather occurs naturally. However, the influence of human activities on global climate is altering the frequency and/or severity of many of these events.

Observations show that heavy downpours have already increased nationally. Regional and global models project increases in extreme precipitation for every U.S. region.[118] Precipitation events tend to be limited by available moisture. For the heaviest, most rare events, there is strong evidence from observations[119] and models[118,120] that higher temperatures and the resulting moister atmosphere are the main cause of these observed and projected increases. Other factors that may also have an influence on observed U.S. changes in extreme precipitation are land-use changes (for example, changes in irrigation[121,122]) and a shift in the number of El Niño events versus La Niña events.

Climate change can also alter the characteristics of the atmosphere in ways that affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an increasing trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms (also referred to as extra-tropical [outside the tropics] cyclones[123]). There is also a northward shift in storms over the U.S.[124] that are often associated with extreme precipitation. This shift is consistent with projections of a warming world.[125] No change in mid-latitude storm intensity or frequency has been detected.

In the tropics, the most important types of storms are tropical cyclones, referred to as hurricanes when they occur in the Atlantic Ocean. Over the 40 years of satellite monitoring, there has been a shift toward stronger hurricanes in the Atlantic, with fewer Category 1 and 2 hurricanes and more Category 4 and 5 hurricanes. There has been no significant trend in the global number of tropical cyclones[126] nor has any trend been identified in the number of U.S. landfalling hurricanes.[1] Two

Extreme Precipitation

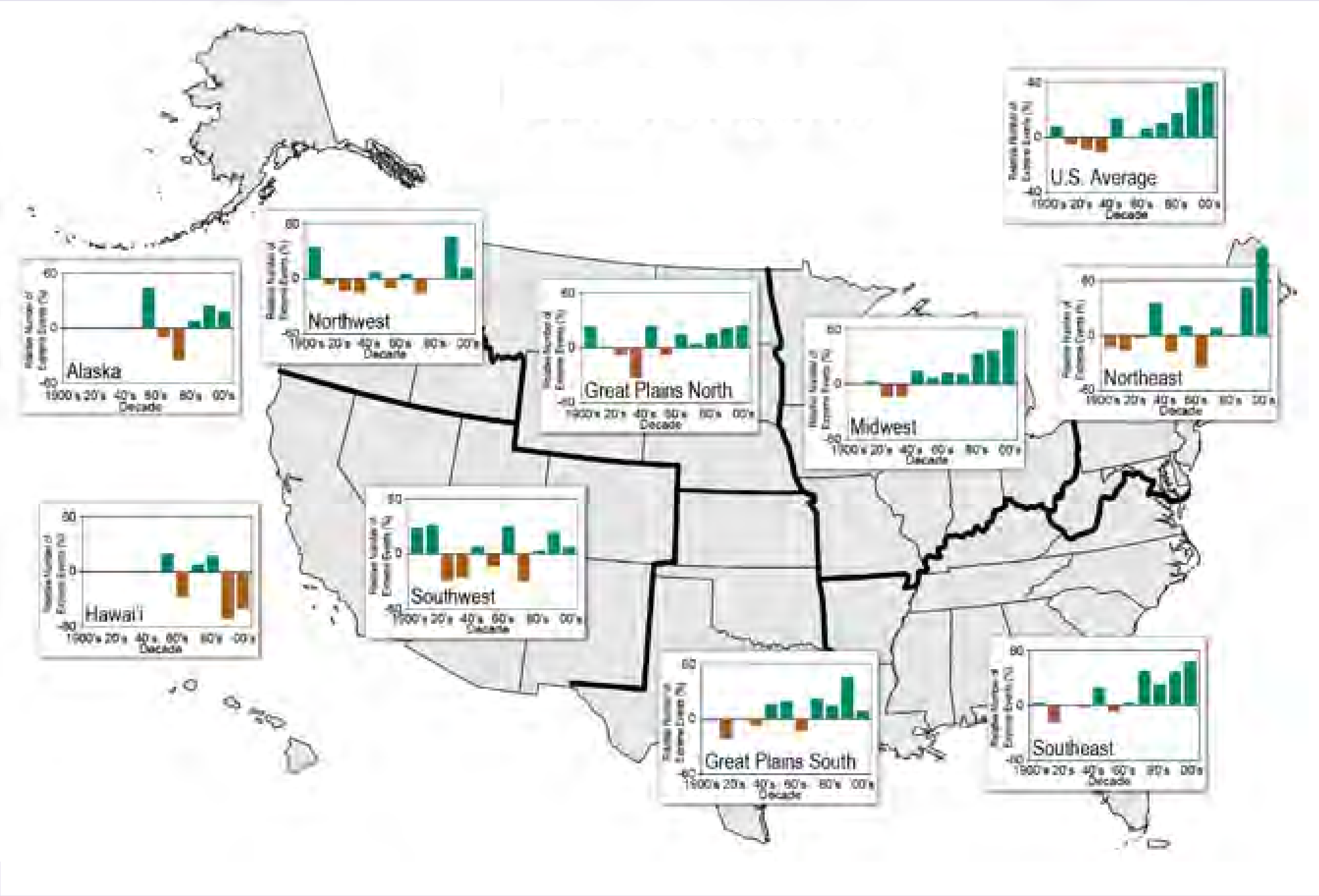


Figure 32. Heavy downpours are increasing nationally, with especially large increases in the Midwest and Northeast.[99] Despite considerable decadal-scale natural variability, indices such as this one based on 2-day precipitation totals exceeding a threshold for a 1-in-5-year occurrence exhibit a greater than normal occurrence of extreme events since 1991 in all U.S. regions except Alaska and Hawaiʻi. Each bar represents that decade's average, while the far right bar in each graph represents the average for the 12-year period of 2001-2012. Analysis is based on 726 long-term, quality-controlled station records. This figure is a regional expansion of the national index in Figure 2.16 of Chapter 2. (Figure source: updated from Kunkel et al. 2013[99]).

studies have found an upward trend in the number of extreme precipitation events associated with tropical cyclones,[127] but significant uncertainties remain.[122] A change in the number of Atlantic hurricanes has been identified, but interpreting its significance is complicated both by multi-decadal natural variability and the reliability of the pre-satellite historical record.[128] The global satellite record shows a shift toward stronger tropical cyclones,[126,129] but does not provide definitive evidence of a long-term trend. Nonetheless, there is a growing consensus based on scientific understanding and very-high-resolution atmospheric modeling that the strongest tropical cyclones, including Atlantic hurricanes, will become stronger in a warmer world.[130]

The number of heat waves has been increasing in recent years. On a decadal basis, the decade of 2001-2010 had the second highest number since 1901 (first is the 1930s). This trend has continued in 2011 and 2012, with the number of intense heat waves being almost triple the long-term average. Regionally, the Northwest, Southwest, and Alaska had their highest number of heat waves in the 2000s, while the 1930s were the highest in the other regions (note that the Alaskan time series begins in the 1950s). For the number of intense cold waves, the national-average value was highest in the 1980s and lowest in the 2000s. The lack of cold waves in the 2000s was prevalent throughout the contiguous U.S. and Alaska. Climate model simulations indicate that the recent trends toward increasing frequency of heat waves and decreasing frequency of cold waves will continue in the future.

The data on the number and intensity of severe thunderstorm phenomena (including tornadoes, thunderstorm winds, and hail) are not of sufficient quality to determine whether there have been historical trends.[119] This scarcity of high-quality data, combined with the fact that these phenomena are too small to be directly represented in climate models,[131] makes it difficult to project how these storms might change in the future.

Supplemental Message 10.

Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.

As temperatures rise, evaporation rates increase, which (all else remaining equal) would be expected to lead to increased drying.[131] The Palmer Drought Severity Index (PDSI),[132] a widely used indicator of dryness that incorporates both precipitation and temperature-based evaporation estimates, does not show any trend for the U.S. as a whole over the past century.[133] However, drought intensity and frequency have been increasing over much of the western United States, especially during the last four decades. In the Southeast, western Great Lakes, and southern Great Plains, droughts have increased during the last 40 years, but do not show an increase when examined over longer periods encompassing the entire last century. In the Southwest, drought has been widespread since 2000; the average value of the PDSI during the 2000s indicated the most severe average drought conditions of any decade. The severity of recent drought in the Southwest reflects both the decade's low precipitation and high temperatures.

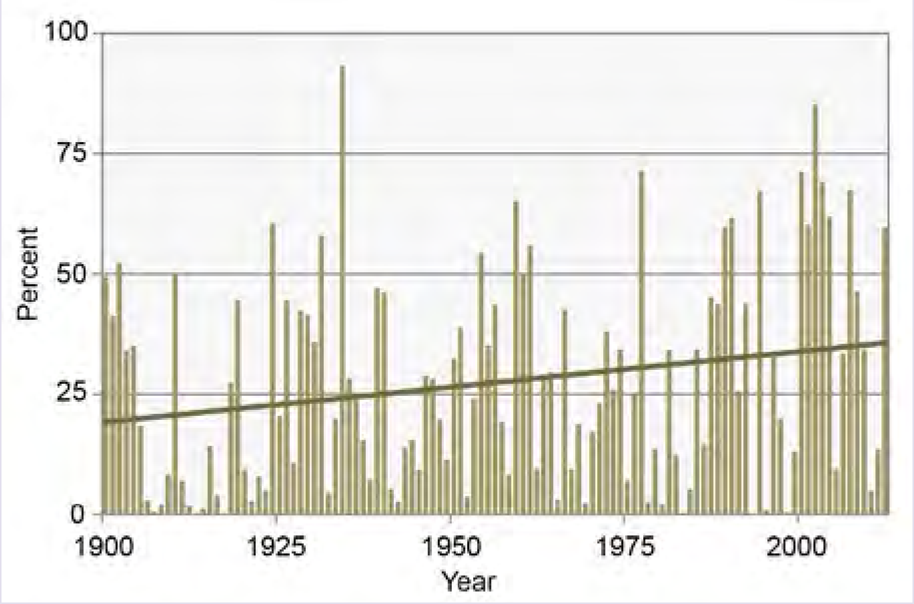

Percent of West in Summer Drought

Figure 33. The area of the western U.S. in moderately to extremely dry conditions during summer (June-July-August) varies greatly from year to year but shows a long-term increasing trend from 1900 to 2012. (Data from NOAA NCDC State of the Climate Drought analysis).

Seasonal and multi-year droughts affect wildfire severity.[134] For example, persistent drought conditions in the Southwest, combined with wildfire suppression and land management practices,[135] have contributed to wildfires of unprecedented size since 2000. Five western states (Arizona, Colorado, Utah, California, and New Mexico) have experienced their largest fires on record at least once since 2000. Much of the increase in fires larger than 500 acres occurred in the western United States, and the area burned in the Southwest increased more than 300% relative to the area burned during the 1970s and early 1980s.[136]

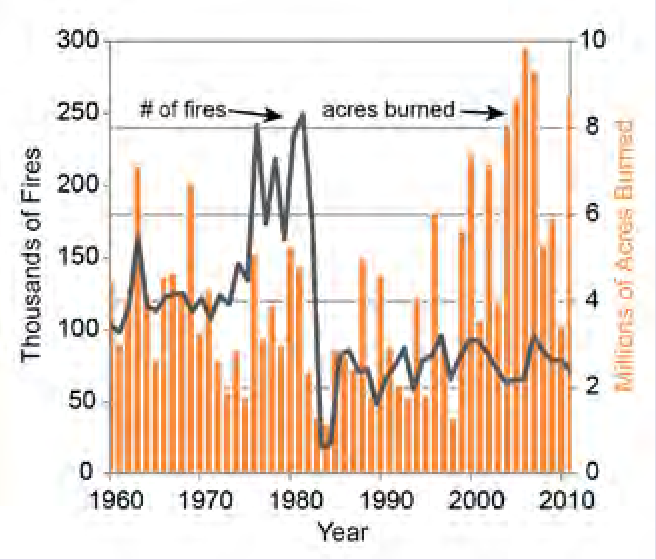

Changing Forest Fires in the U.S.

Figure 34. Although the average number of wildfires per year (black line) has decreased over time, the total area burned by wildfires (orange bars) in the continental U.S. (primarily in the western states) has nearly doubled since 2000 relative to the long-term 1960-1999 average (data shown are for 1960-2011). (Data from the National Interagency Fire Center).

Droughts on a duration and scale that affect agriculture are projected to increase in frequency and severity in this century due to higher temperatures. Projections of the Palmer Drought Severity Index at the end of this century indicate that the normal state for most of the nation will be what is considered moderate to severe drought today.[137,138] The PDSI is used by several states for monitoring drought and for triggering certain actions.[139] It is also one component of the U.S. Drought Monitor.[140] The closely related Palmer Hydrological Index is the most

Extreme Drought in the U.S. and Mexico, Past and Future

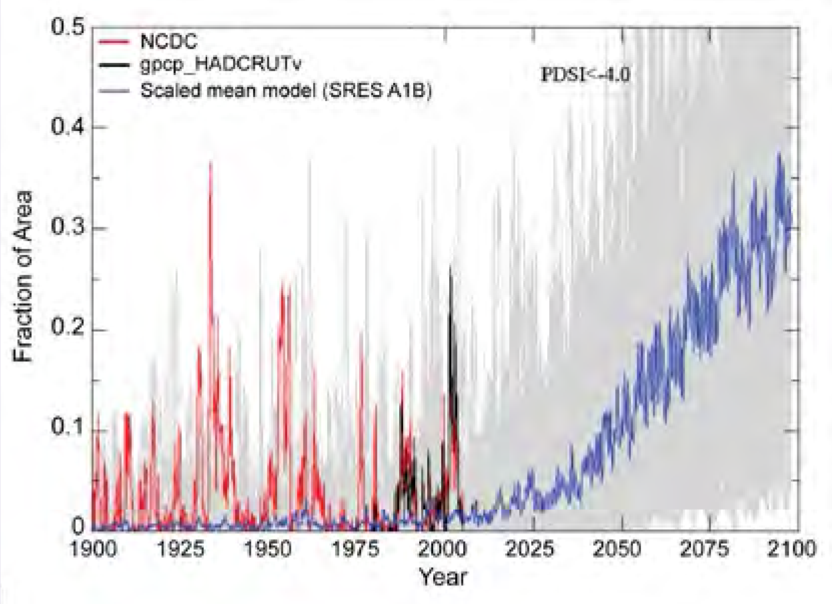


Figure 35. The fractional areal extent of the contiguous U.S. and Mexico in extreme drought according to projections of the Palmer Drought Severity Index under an intermediate emissions scenario (SRES A1B, in between the B1 and A2 scenarios used elsewhere in this report) (Supplemental Message 5 and Ch. 2: Our Changing Climate, Key Message 3). The Palmer Drought Severity Index is the most widely used measure of drought, although it is more sensitive to temperature than other drought indices and may over-estimate the magnitude of drought increases. The red line is based on observed temperature and precipitation. The blue line is from the average of 19 different climate models. The gray lines in the background are individual results from over 70 different simulations from these models. These results suggest an increasing probability of agricultural drought over this century throughout most of the U.S. (Figure source: Wehner et al. 2011[138]).

important component of NOAA's Objective Long-term Drought Indicator Blend,[141] which is used by the U.S. Department of Agriculture to identify counties that are eligible to participate in certain Federal Government drought relief programs. The U.S. Drought Monitor is used by some states for similar purposes.

Despite its widespread usage, the PDSI may be overly sensitive to future temperature increases.[142] As temperatures increase during this century, these PDSI-based monitoring tools may over-estimate the intensity of drought during anomalous warm periods, so statutory adjustments to these tools may be warranted. However, the projection of increased drought risk is reinforced by a direct examination of future soil moisture content projections, which reveals substantial drying in most areas of the western U.S (Ch. 2: Our Changing Climate, Key Message 3).

Provided the wood and ground litter has dried out, the area of forest burned in many mid-latitude areas, including the western United States, may increase substantially as temperature and evapotranspiration increase, exacerbating drought.[143] Under even relatively modest amounts of warming, significant increases in area burned are projected in the Sierra Nevada, southern Cascades, and coastal California; in the mountains of Arizona and New Mexico; on the Colorado Plateau; and in the Rocky Mountains.[144] Other studies, examining a broad range of climate change and development scenarios, find increases in the chance of large fires for much of northern California's forests.[145]

Long periods of consecutive days with little or no precipitation also can lead to drought. The average annual maximum number of consecutive dry days are projected to increase for the higher emissions scenarios in areas that are already prone to little precipitation by mid-century and increase thereafter (Ch. 2: Our Changing Climate, Key Message 5). Much of the western and southwestern U.S. is projected to experience statistically significant increases in the annual maximum number of consecutive dry days, on average up to 10 days above present-day values for parts of the contiguous U.S. by the end of this century under high emissions scenarios. Hence, some years are projected to experience substantially longer dry seasons.

Change in Maximum Number of Consecutive Dry Days

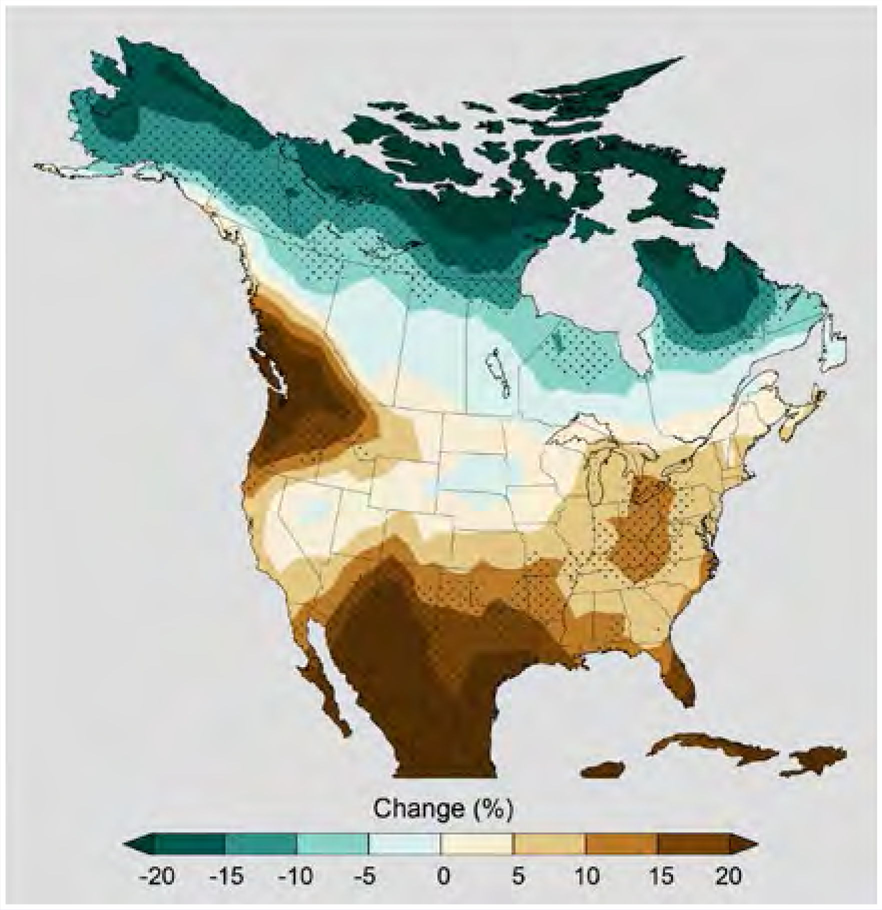


Figure 36. Change in the number of consecutive dry days (days receiving less than 0.04 inches (1 mm) of precipitation) at the end of this century (2081-2100) relative to the end of last century (1980-1999) under the higher scenario, RCP 8.5. Stippling indicates areas where changes are consistent among at least 80% of the 25 models used in this analysis. (Supplemental Message 5 and Ch. 2: Our Changing Climate, Key Message 3). (Figure source: NOAA NCDC / CICS-NC).

Supplemental Message 11.

Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.

Increasing temperatures and associated impacts are apparent throughout the Arctic, including Alaska. Sea ice coverage and thickness, permafrost on land, mountain glaciers, and the Greenland Ice Sheet all show changes consistent with higher temperatures.

The most dramatic decreases in summer sea ice have occurred along the northern coastline of Alaska and Russia. Since the satellite record began in 1979, September (summer minimum) sea ice extent has declined by 13% per decade in the Beaufort Sea and 32% per decade in the Chukchi Sea,[146] leaving the Chukchi nearly ice-free in the past few Septembers. Longer-term records based on climate proxies suggest that pan-Arctic ice extent in summer is the lowest it has been in at least the past 1,450 years.[147] Winter ice extent has declined less than summer ice extent (see Ch. 2: Our Changing Climate, Key Message 11), indicative of a trend toward seasonal-only (as opposed to year-round) ice cover, which is relatively thin and vulnerable to melt in the summer. Recent work has indicated that the loss of summer sea ice may be affecting the atmospheric circulation in autumn and early winter. For example, there are indications that a weakening of subpolar westerly winds during autumn is an atmospheric response to a warming of the lower troposphere of the Arctic.[148] Extreme summer ice retreat also appears to be increasing the persistence of associated mid-latitude weather patterns, which may lead to an increased prob-

Arctic Sea Ice Decline

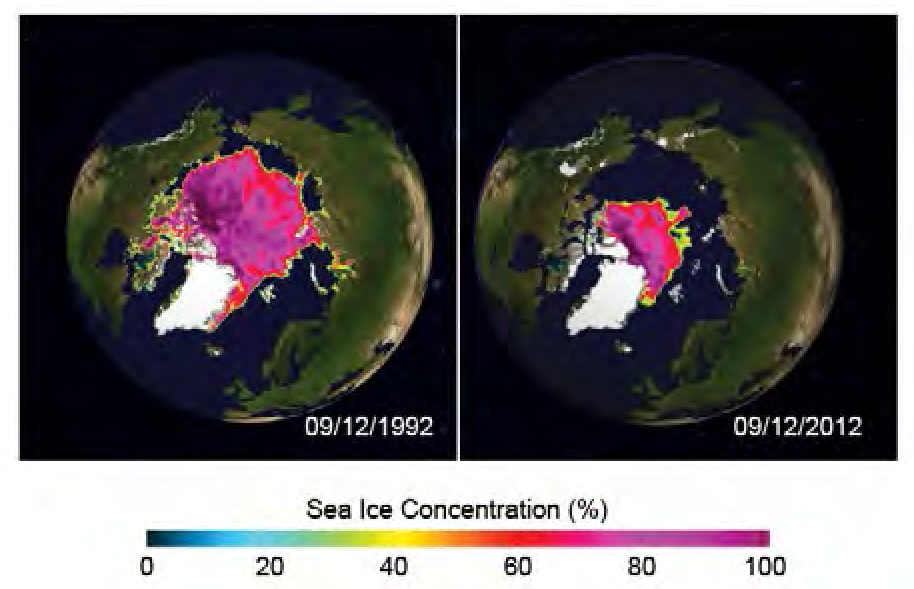


Figure 37. The spatial extent of Arctic sea ice cover in September has decreased substantially in the past two decades, as shown in this pair of satellite images depicting sea ice concentrations. The reduction of September sea ice extent from 1992 (left) to 2012 (right) has been nearly 50%, or about 1.2 million square miles (3 million square kilometers), which is nearly one-third the area of the contiguous United States. (Figure source: University of Illinois, The Cryosphere Today;[150] Data from the National Snow and Ice Data Center).

ability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves.[149] However, the combination of interannual variability and the small sample of years with extreme ice retreat make it difficult to identify a geographically consistent atmospheric response pattern in the middle latitudes.

On land, changes in permafrost provide compelling indicators of a warming climate, as they tend to reflect long-term average changes in climate. Borehole measurements are particularly useful, as they provide information from levels below about 10-meter depth where the seasonal cycle becomes negligible. Increases in borehole temperatures over the past several decades are apparent at various locations, including Alaska, northern Canada, Greenland, and northern Russia. The increases are about 3.6°F at the two stations in northern Alaska (Deadhorse and West Dock). In northern Alaska and northern Siberia, where permafrost is cold and deep, thaw of the entire permafrost layer is not imminent. However, in the large areas of discontinuous permafrost of Russia, Alaska, and Canada, average annual temperatures are sufficiently close to freezing that permafrost thaw is a risk within this century. Thawing of permafrost can release methane into the atmosphere, amplifying warming (see Supplemental Message 5), as well as potentially causing infrastructure and environmental damages.

There is evidence that the active layer (the near-surface layer of seasonal thaw, typically up to three feet deep) may be thickening in many areas of permafrost, including in northern Russia and Canada.[152] Permafrost thaw in coastal areas increases the vulnerability of coastlines to erosion by ocean waves, which in turn are exacerbated by the loss of sea ice from coastal areas affected by storms.

Increased melt is reducing both the mass and areal extent of glaciers over much of the Northern Hemisphere. Over the past decade, the contribution to sea level rise from glaciers and small ice caps (excluding Greenland) has been comparable to the contributions from the Greenland Ice Sheet.[153]

Projections of future mass loss by glaciers and small ice caps indicate a continuation of current trends, although these projections are based only on the changes in temperature and precipitation projected by global climate models; they do not include the effects of dynamical changes (for example, glacier movement). While there is a wide range among the projections derived from different global climate models, the models are consistent in indicating that the effects of melting will outweigh the effects of increases in snowfall. The regions from which the contributions to sea level rise are projected to be largest are the Canadian Arctic, Alaska, and the Russian Arctic.[151]

Permafrost Temperatures Rising

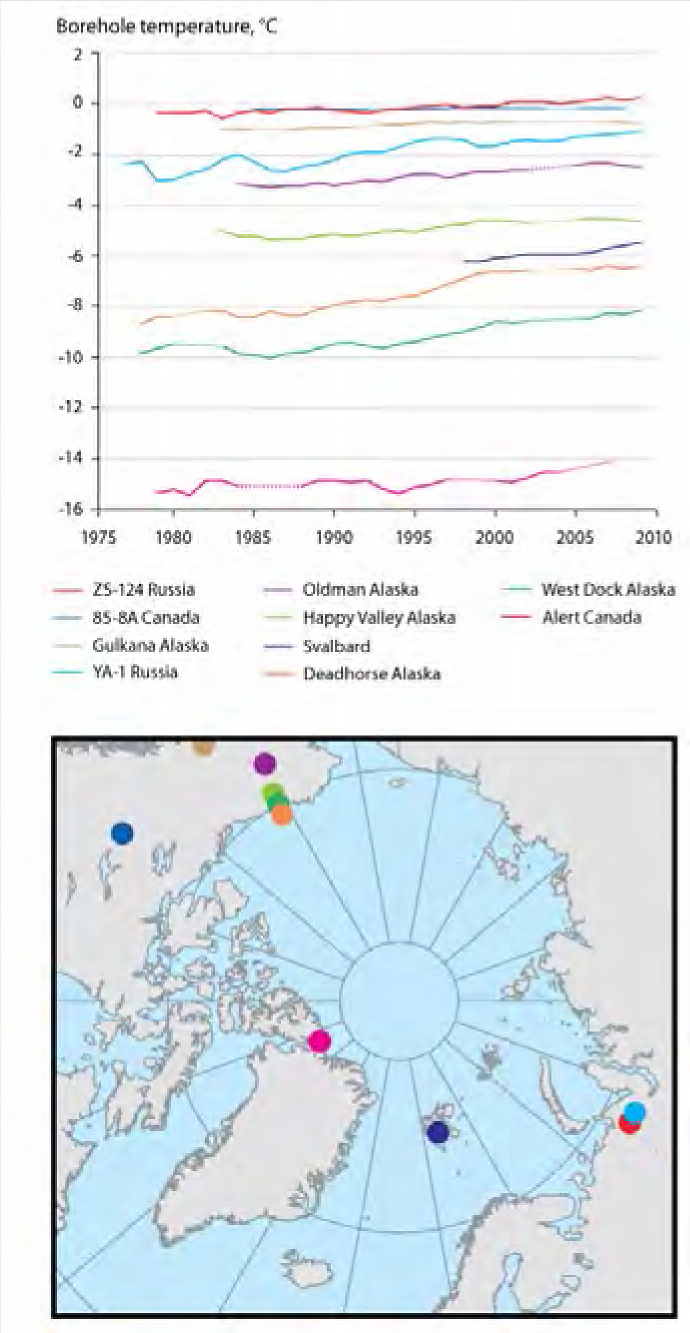


Figure 38. Ground temperatures at depths between 33 and 66 feet (10 and 20 meters) for boreholes across the circumpolar northern permafrost regions. Lower panel shows locations of measurement sites in colors corresponding to lines in upper panel (Figure source: AMAP 2011[151]).

Melting of Arctic Land-based Ice

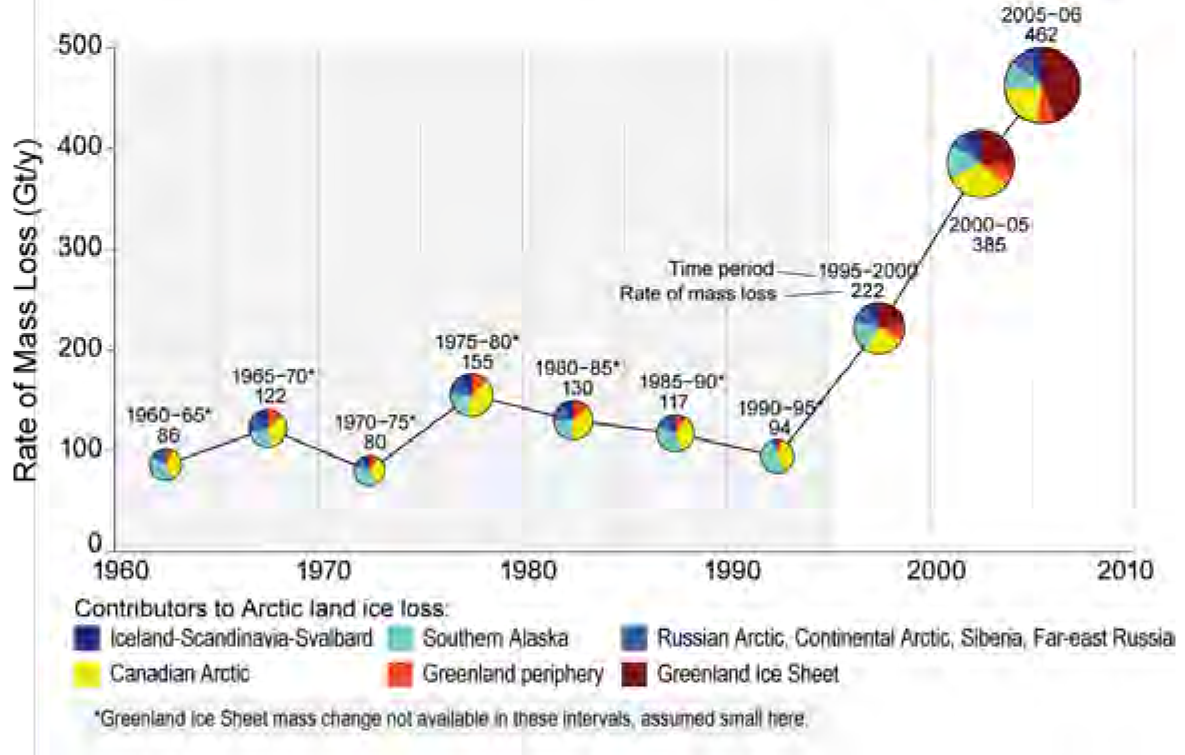


Figure 39. Inputs of freshwater to the ocean from mountain glaciers, small ice caps, and the Greenland Ice Sheet have increased dramatically in the past two decades. The size of the circles in the figure is proportional to the five-year average freshwater contributions to the ocean from melting of land-based ice. The coloring indicates the relative contributions from the Greenland Ice Sheet (brown) and mountain glaciers from the Greenland periphery (orange), Iceland-Scandinavia-Svalbard (dark blue), the Canadian Arctic (yellow), southern Alaska (light blue), and the Russian Arctic (medium blue). The largest contributions from mountain glaciers have been from the Canadian Arctic and southern Alaska. Note that contributions from mass changes of the Greenland Ice Sheet are not available prior to the mid-1990s, but they are assumed to have been small during this earlier period because annual snow accumulation was in approximate balance with annual meltwater discharge. (Figure source: AMAP 2011[151]).

On the left is a photograph of Muir Glacier in Alaska taken on August 13, 1941; on the right, a photograph taken from the same vantage point on August 31, 2004. Total glacial mass has declined sharply around the globe, adding to sea level rise. (Left photo by glaciologist William O, Field; right photo by geologist Bruce F. Molnia of the United State Geological Survey.)

Melting Glaciers Lead to Sea Level Rise

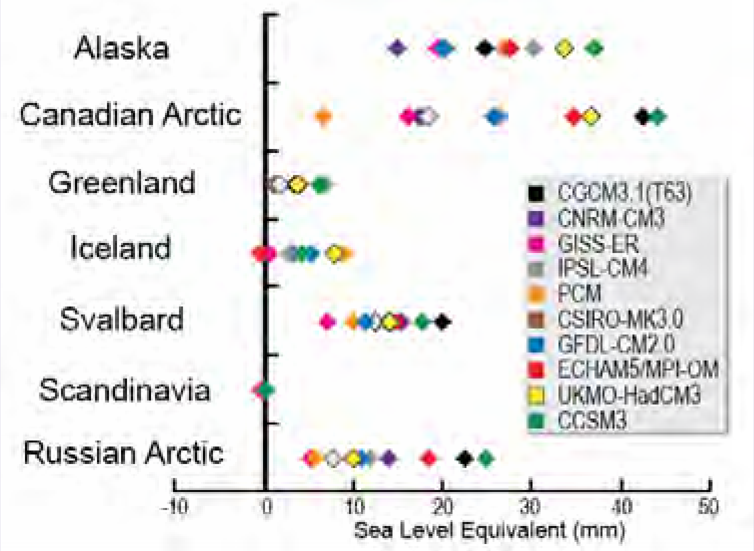


Figure 40. Projections of contributions to sea level rise by 2100 for seven regions that include all Arctic glaciers. Projections are based on temperature and precipitation simulated by ten different global climate models from CMIP3. For each region, the estimates are shown in different colors corresponding to the ten different models. (Figure source: adapted from Radić and Hock 2011[154]).

Supplemental Message 12.

Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

The rising global average sea level is one of the hallmarks of a warming planet. It will also be one of the major impacts of human-caused global warming on both human society and the natural environment.

Global sea level is increasing as a result of two different processes. First, the oceans absorb more than 90% of the excess heat trapped by human interference with the climate system, and this warms the oceans.[155] Like mercury in a thermometer, the warmer ocean water expands, contributing to global sea level rise. Second, the warmer climate also causes melting of glaciers and ice sheets. This meltwater eventually runs off into the ocean and contributes to sea level rise as well. A recent synthesis of surface and satellite measurements of the ice sheets shows that the rate at which the Greenland and Antarctic ice sheets contribute to sea level rise has been increasing rapidly and has averaged 0.02 inches (plus or minus 0.008) per year since 1992, with Greenland's contribution being more than double that of Antarctica.[156] In addition, local sea level change can differ from the global average sea level rise due to changes in ocean currents, local land movement, and even changes in the gravitational pull of the ice sheets and changes in Earth's rotation.

There is high confidence that global sea level will continue to rise over this century and beyond and that most coastlines will see higher water levels. The rates of sea level rise along individual coastlines are difficult to predict, as they can vary depending on the region. For example, globally averaged sea level has risen steadily by about 2.4 inches over the past two decades. But during that time, many regions have seen much more rapid rise while some have experienced falling sea levels. These complicated patterns are caused by changes in ocean currents and movement of heat within the oceans. Many of these patterns are due in part to natural, cyclic changes in the oceans. On the West Coast of the United States, sea level has fallen slightly since the early 1990s. Recent work suggests that a natural cycle known as the Pacific Decadal Oscillation has counteracted most or all of the global sea level signal there. This means that in coming decades the West Coast is likely to see faster than average sea level rise as this natural cycle changes phase.[157]

Along any given coastline, determining the rate of sea level rise is complicated by the fact that the land may be rising or sinking. Along the Gulf Coast, for example, local geological factors including extraction of oil, natural gas, and water from underground reservoirs are causing the land to sink, which could increase the effect of global sea level rise by several inches by the end of this century.[158] In some other locations, coastlines are rising as they continue to rebound from glaciation during the last glacial maximum. Predicting the future of any single coastline requires intimate knowledge of the local geology as well as the processes that cause sea levels to change at both the local and global scale.

Greenland and Antarctica hold enough ice to raise global sea levels by more than 200 feet if they were to melt completely. While this is very unlikely over at least the next few centuries, studies suggest that meltwater from ice sheets could contribute anywhere from several inches to 4.5 feet to global sea levels by the end of this century.[159] Because their behavior in a warming climate is still very difficult to predict, these two ice sheets are the biggest wildcards for potential sea level rise in the coming decades. What is certain is that these ice sheets are already responding to the warming of the oceans and the atmosphere. Satellites that measure small changes in the gravitational pull of these two regions have proven that both Greenland and Antarctica are currently losing ice and contributing to global sea level rise.[160]

In the United States, an estimated 5 million people currently live within 4 feet of current high tide lines, which places them at increasing risk of flooding in the coming decades.[161] Although sea level rise is often thought of as causing a slow inundation, the most immediate impacts of sea level rise are increases in high tides and storm surges. A recent assessment of flood risks in the United States found that the odds of experiencing a "100-year flood" are on track to double by 2030.

Sea Level Rise, 1993-2012

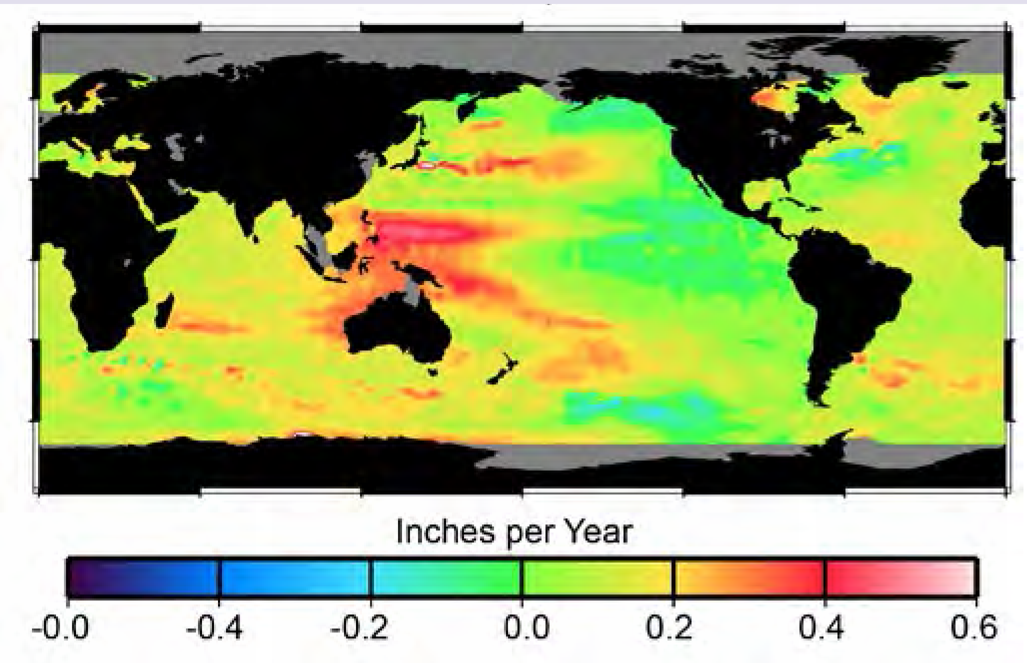


Figure 41. The patterns of sea level rise between 1993 and 2012 as measured by satellites. The complicated patterns are a reminder that sea levels do not rise uniformly.[162] (Figure source: University of Colorado, Sea Level Research Group).

Ice Loss from Greenland and Antarctica

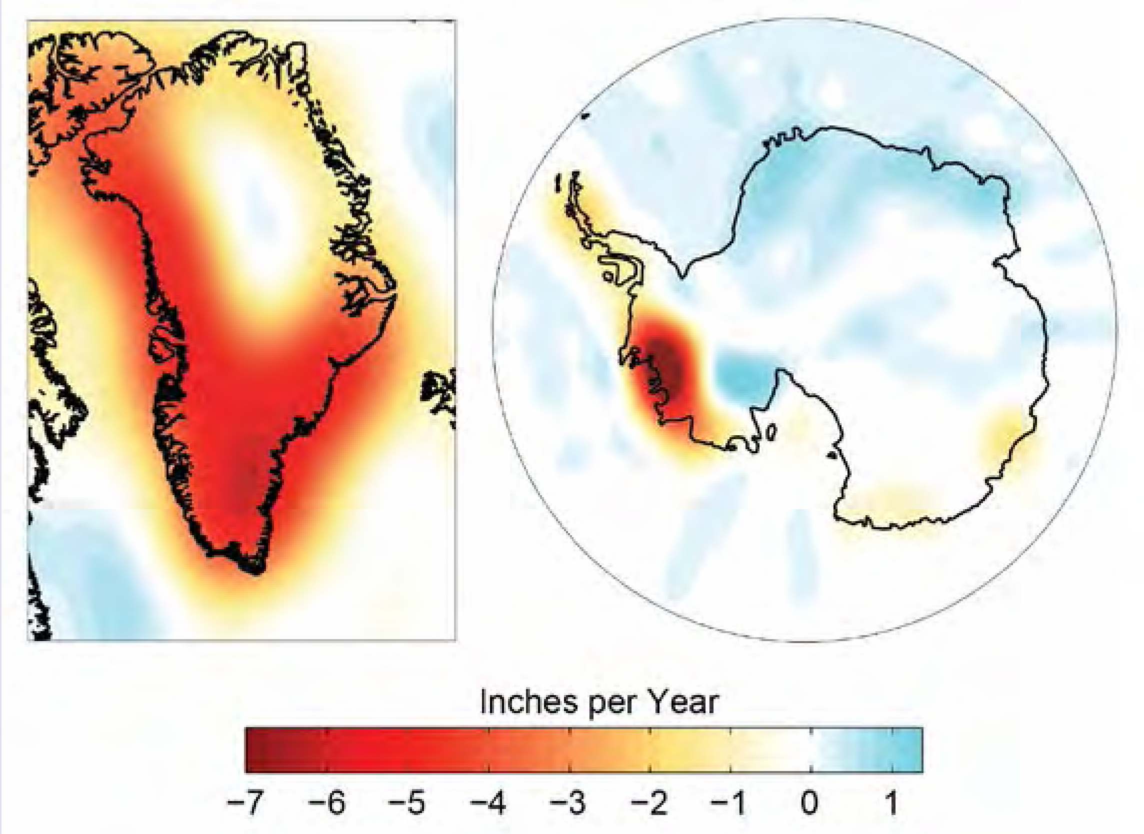


Figure 42. Rate of local ice sheet mass loss (in inches of water-equivalent-height per year) from Greenland (left) and Antarctica (right) from 2003 to 2012. The GRACE (Gravity Recovery and Climate Experiment) satellites measure changes in the pull of gravity over these two regions. As they lose ice to the oceans, the gravitational pull of Greenland and Antarctica is reduced. Analyses of GRACE data have now proven that both of the major ice sheets are currently contributing to global sea level rise due to ice loss. Over the periods plotted here, Greenland lost enough ice to raise sea level at a rate of 0.028 inches per year (0.72 mm/yr), and Antarctica lost ice at a rate that caused 0.0091 inches of sea level rise per year (0.24 mm/yr). (Figure source: NASA Jet Propulsion Laboratory, (left) updated from Velicogna and Wahr 2013;[163] (right) updated from Ivins et al. 2013[164]).

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APPENDIX 4
FREQUENTLY ASKED QUESTIONS

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On the Web: http://nca2014.globalchange.gov/report/appendices/faqs

FAQ INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

APPENDIX 4 FREQUENTLY ASKED QUESTIONS

This section answers some frequently asked questions about climate change. The questions addressed range from those purely related to the science of climate change to those that extend to some of the issues being faced in consideration of mitigation and adaptation measures. The author team selected these questions based on those often asked in presentations to the public. The answers are based on peer-reviewed science and assessments and have been confirmed by multiple analyses.

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

B. Is the climate changing? How do we know?

C. Climate is always changing. How is recent change different than in the past?

D. Is the globally averaged surface temperature still increasing? Isn't there recent evidence that it is actually cooling?

E. Is it getting warmer at the same rate everywhere? Will the warming continue?

F. How long have scientists been investigating human influences on climate?

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

H. Could the sun or other natural factors explain the observed warming of the past 50 years?

I. How do we know that human activities are the primary cause of recent climate change?

J. What is and is not debated among climate scientists about climate change?

K. Is the global surface temperature record good enough to determine whether climate is changing?

L. Is Antarctica gaining or losing ice? What about Greenland?

M. Weren't there predictions of global cooling in the 1970s?

N. How is climate projected to change in the future?

O. Does climate change affect severe weather?

P. How are the oceans affected by climate change?

Q. What is ocean acidification?

R. How reliable are the computer models of the Earth's climate?

S. What are the key uncertainties about climate change?

T. Are there tipping points in the climate system?

U. How is climate change affecting society?

V. Are there benefits to warming?

W. Are some people more vulnerable than others?

X. Are there ways to reduce climate change?

Y. Are there advantages to acting sooner rather than later?

Z. Can we reverse global warming?

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

Predicting how climate will change in future decades is a different scientific issue from predicting weather a few weeks from now. Weather is short term and chaotic, largely determined by whatever atmospheric system is moving through at the time, and thus it is increasingly difficult to predict day-to-day changes beyond about two weeks into the future. Climate, on the other hand, is a long-term statistical average of weather and is determined by larger-scale forces, such as the level of heat-trapping gases in the atmosphere and the energy coming from the sun. Thus it is actually easier to project how climate will change in the future. By analogy, while it is impossible to predict the age of death of any individual, the average age of death of an American can be calculated. In this case, weather is like the individual, while climate is like the average. To extend this analogy into the realm of climate change, we can also calculate the life expectancy of the average American who smokes. We can predict that on average, a smoker will not live as long as a non-smoker. Similarly, we can project what the climate will be like if we emit less heat-trapping gas, and what it will be like if we emit more.

Weather is the day-to-day variations in temperature, precipitation, and other aspects of the atmosphere around us. Weather prediction using state-of-the-art computer models can be very accurate for a few days to more than a week in advance. Because weather forecasts are based on the initial conditions of the atmosphere and ocean at the time the prediction is made, accuracy decays over time. After about two weeks, the effects of small errors in defining these initial conditions grow so large that meteorologists can no longer discern what the weather will be like on any specific day or place.

Climate is long-term average weather – the statistics of weather over long time scales, typically of 30 years or more. Climate is primarily the result of the effects of local geography, such as distance from the equator, distance from the ocean, and local topography and elevation, combined with larger scale climate factors that can change over time. These include the amount of energy from the sun and the composition of the atmosphere, including the amount of greenhouse gases and tiny particles suspended in the atmosphere. Knowing all these factors enables scientists to quantify the climate at a given place and time. Climate change occurs when these large-scale climate factors change over time.

Using our understanding of the physics of how the atmosphere works, we can estimate how climate will change in the future – in response to human activities, which are now changing Earth's atmospheric composition faster than at any time in at least the last 800,000 years. It is also possible to estimate changes in the statistics of certain types of weather events, such as heat waves or heavy precipitation events, especially when we know what is causing them to change.

We know how climate has changed in the recent past, and often we know why those changes have occurred. For example, the increase in global temperature, or global warming, that has occurred over the last 150 years can only be explained if we include the impact of increasing levels of heat-trapping gases in the atmosphere caused by human activities. The present generation of climate models can successfully reproduce the past warming and therefore provide an essential tool to peer into the future.

The role of human activities in driving recent change is discussed in FAQ I. (In the context of a changing climate, the term "human activities" is used throughout these frequently asked questions to refer specifically to activities, such as extracting and burning fossil fuels, deforestation, agriculture, waste treatment, and so on, that produce heat-trapping gases like carbon dioxide, methane, and nitrous oxide and/or emissions of black carbon, sulfate, and other particles.) Other human activities, like changes in land use, can also alter climate, especially on local or regional scales, such as that which occurs with urban heat islands.

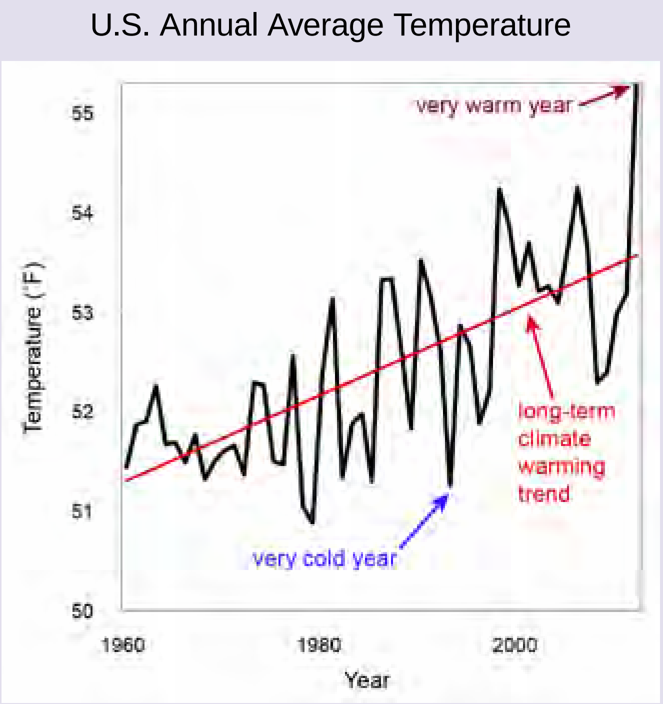


Figure 1. Climate change refers to the changes in average weather conditions that persist for an extended period of time, over multiple decades or even longer. Year-to-year and even decade-to-decade conditions do not necessarily tell us much about long-term changes in climate. One cold year, or even a few cold years in a row, does not contradict a long-term warming trend, even as one hot year does not prove it. (Figure source: adapted from Kunkel et al. 2013[1]).

B. Is the climate changing? How do we know?

Yes. The world has warmed over the last 150 years, and that warming has triggered many other changes to the Earth's climate. Evidence for a changing climate abounds, from the top of the atmosphere to the depths of the oceans. Changes in surface, atmospheric, and oceanic temperatures; melting glaciers, snow cover, and sea ice; rising sea level; and increase in atmospheric water vapor have been documented by hundreds of studies conducted by thousands of scientists around the world. Rainfall patterns and storms are changing and the occurrence of droughts is shifting.

Documenting climate change often begins with global average temperatures recorded near Earth's surface, where people live. But these temperatures, recorded by weather stations, are only one indicator of climate change. Additional evidence for a warming world comes from a wide range of consistent measurements of the Earth's climate system. It is the sum total of these indicators that lead to the conclusion that warming of our planet is unequivocal.

Evidence for a changing climate is not confined to the Earth's surface. Measurements by weather balloons and satellites consistently show that the temperature of the troposphere – the lowest layer of the atmosphere – has increased. The temperature of the upper atmosphere, particularly the stratosphere, has cooled, consistent with expectations of changes due to increasing concentrations of CO_2 and other greenhouse gases. The upper ocean has warmed, and more than 90% of the additional energy absorbed by the climate system since the 1960s has been stored in the oceans. As the oceans warm, seawater expands, causing sea level to rise.

As the troposphere warms, Arctic ice and glaciers melt, also causing sea level to rise. About 90% of the glaciers and land-based ice sheets worldwide are melting as the Earth warms, adding further to the sea level rise. Spring snow cover has decreased across the Northern Hemisphere since the 1950s. There have been substantial losses in sea ice in the Arctic Ocean, particularly at the end of summer when sea ice extent is at a minimum (see FAQ L for discussion of Antarctic sea ice).

Warmer air, on average, contains more water vapor. Globally, the amount of water vapor in the atmosphere has increased over the land and the oceans over the last half century. In turn, many parts of the planet have seen increases in heavy rainfall events. All of these indicators and all of the independent data sets for each indicator unequivocally point to the same conclusion: from the ocean depths to the top of the troposphere, the world has warmed and the climate has reacted to that warming.

Ten Indicators of a Warming World

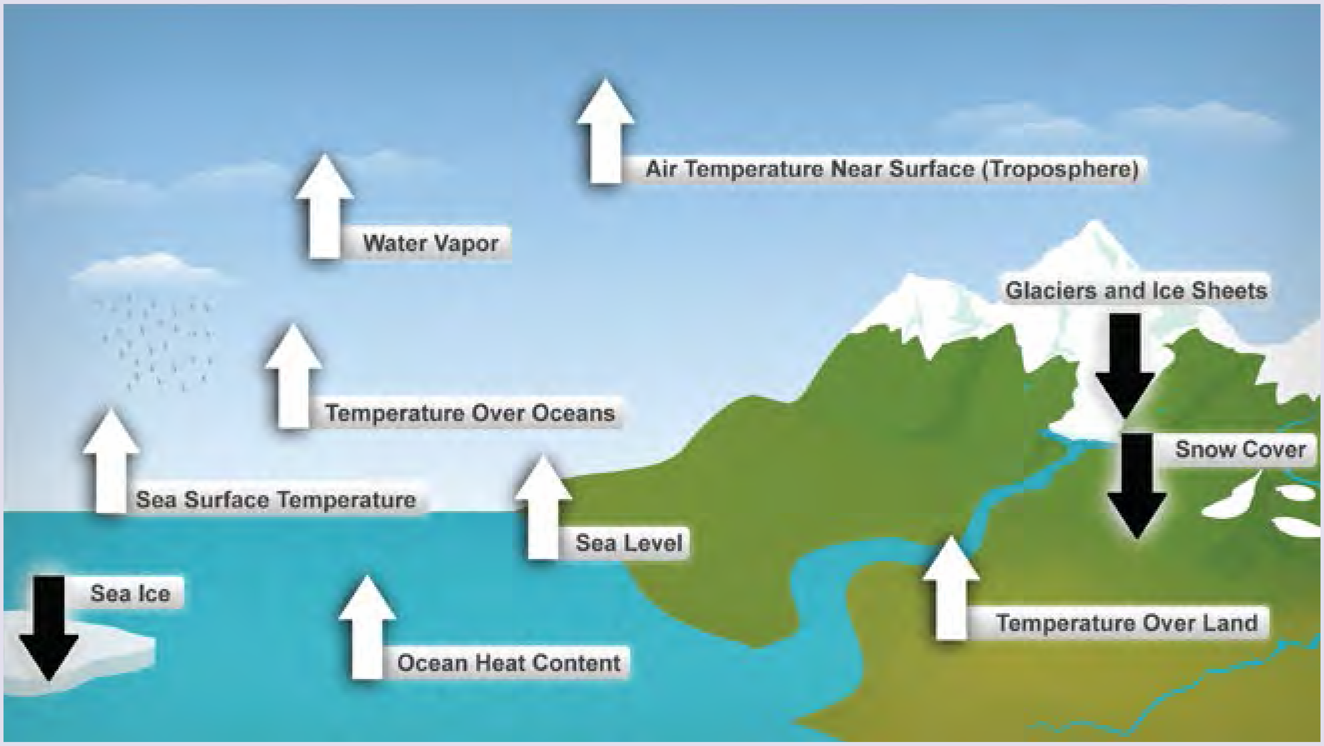


Figure 2. These are just some of the many indicators measured globally over many decades that demonstrate that the Earth's climate is warming. White arrows indicate increases, and black arrows show decreases. All the indicators expected to increase in a warming world are increasing, and all those expected to decrease in a warming world are decreasing. See Figure 3 for measurements showing these trends. (Figure source: NOAA NCDC; based on data updated from Kennedy et al. 2010[2]).

In summary, the evidence that climate is changing comes from a multitude of independent observations. The evidence that climate is changing because of human activity, as discussed in FAQ I and in more detail in Chapter 2: Our Changing Climate and Appendix 3: Climate Science Supplement, comes from observations, basic physics, and analyses from modeling studies.

Indicators of Warming from Multiple Data Sets

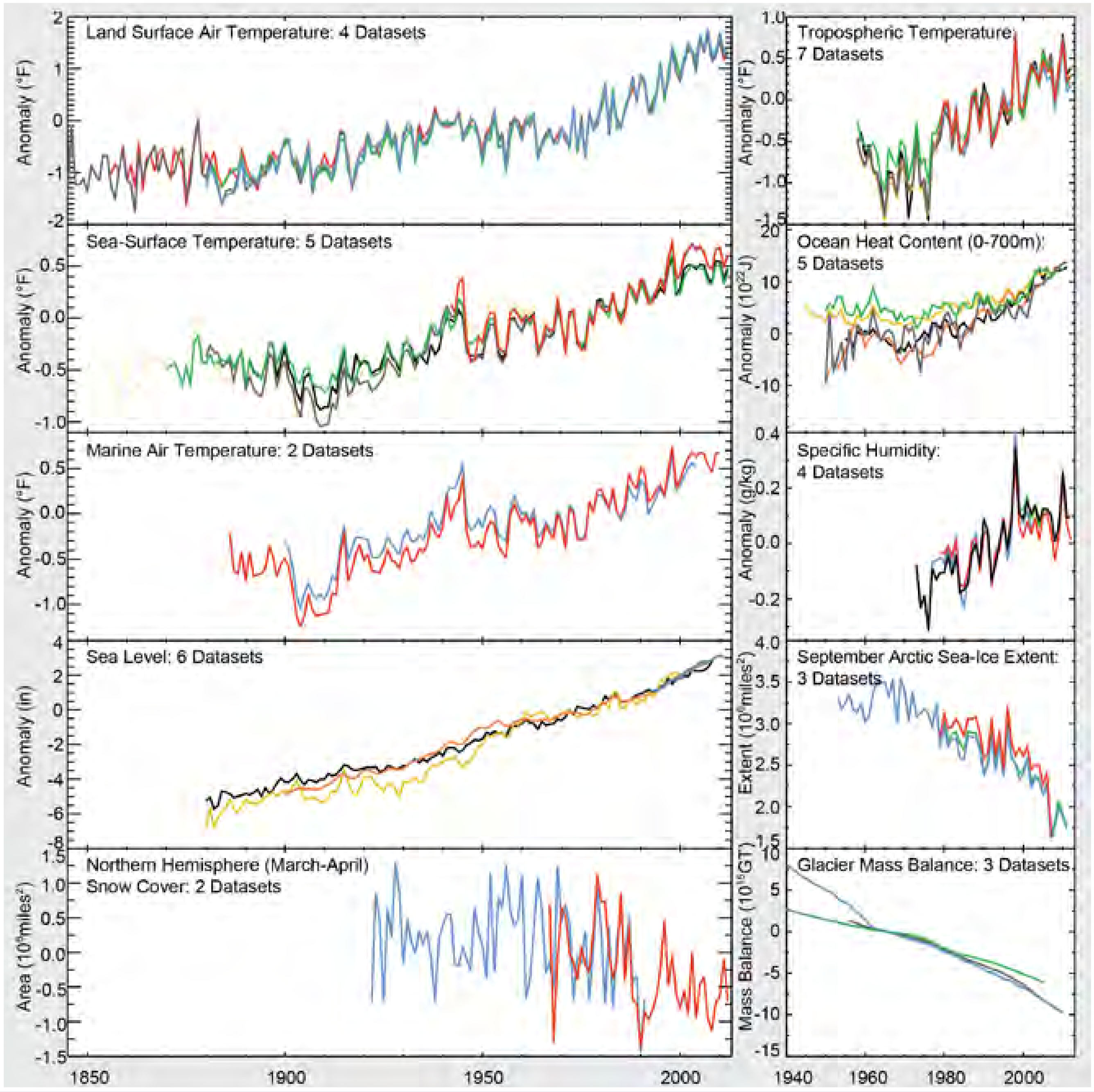


Figure 3. This figure summarizes some of the many datasets documenting changes in the Earth's climate, all of which are consistent with a warming planet. In all figures except the lower two in the right column, data are plotted relative to averages over the period 1960-1999 (Figure source: updated from Kennedy et al. 2010[2]).

C. Climate is always changing. How is recent change different than in the past?

The Earth has experienced many large climate changes in the past. However, current changes in climate are unusual for two reasons: first, many lines of evidence demonstrate that these changes are primarily the result of human activities (see Question I for more info); and second, these changes are occurring (and are projected to continue to occur) faster than many past changes in the Earth's climate.

In the past, climate change was driven exclusively by natural factors: explosive volcanic eruptions that injected reflective particles into the upper atmosphere, changes in energy from the sun, periodic variations in the Earth's orbit, natural cycles that transfer heat between the ocean and the atmosphere, and slowly changing natural variations in heat-trapping gases in the atmosphere. All of these natural factors, and their interactions with each other, have altered global average temperature over periods ranging from months to thousands of years. For example, past glacial periods were initiated by shifts in the Earth's orbit, and then amplified by resulting decreases in atmospheric levels of carbon dioxide and subsequently by greater reflection of solar radiation by ice and snow as the Earth's climate system responded to a cooler climate. Some periods in the distant past were even warmer than what is expected to occur from human-induced global warming. But these changes in the distant past generally occurred much more slowly than current changes.

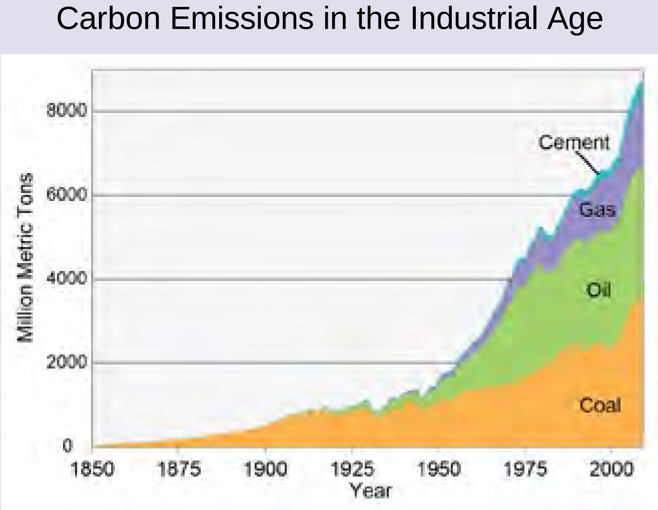


Figure 4. Global carbon emissions from burning coal, oil, and gas and from producing cement (1850-2009). These emissions account for about 80% of the total emissions of carbon from human activities, with land-use changes (like cutting down forests) accounting for the other 20% in recent decades. (Data from Boden et al. 2012[3]).

Natural factors are still affecting the planet's climate today. The difference is that, since the beginning of the Industrial Revolution, humans have been increasingly affecting global climate, to the point where we are now the primary cause of recent and projected future change.

Records from ice cores, tree rings, soil boreholes, and other forms of "natural thermometers," or "proxy" climate data, show that recent climate change is unusually rapid compared to past changes. After a glacial maximum, the Earth typically warms by about 7°F to 13°F over thousands of years (with periods of rapid warming alternating with periods of slower warming, and even cooling, during that time). The observed rate of warming over the last 50 years is about eight times faster than the average rate of warming from a glacial maximum to a warm interglacial period.

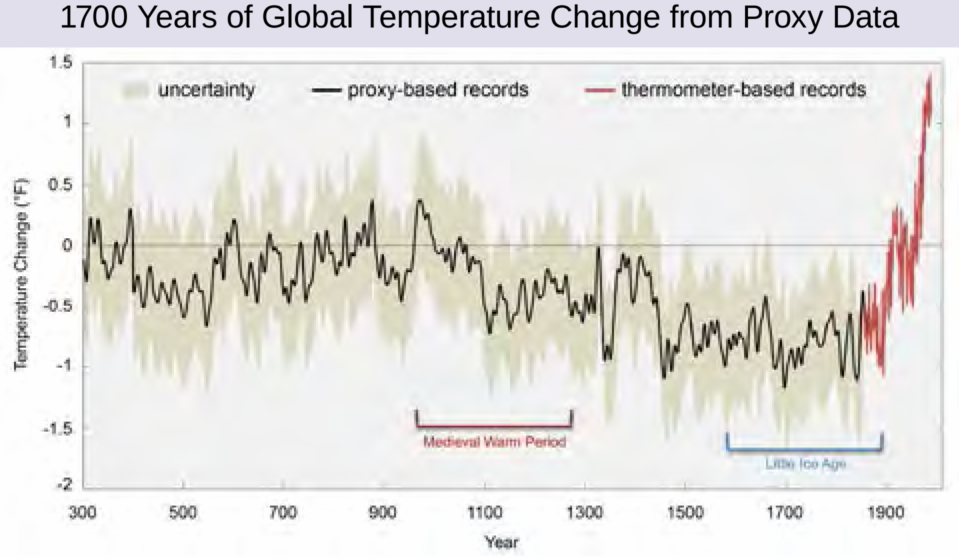


Figure 5. Changes in the temperature of the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961-1990 average temperature. These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years and that the last decade (2001 to 2010) was the warmest decade on record. (Figure source: adapted from Mann et al. 2008[4]).

Global temperatures over the last 100 years are unusually high when compared to temperatures over the last several thousand years. Atmospheric carbon dioxide levels are currently higher than any time in at least the last 800,000 years. Paleoclimate studies indicate that temperature and atmospheric carbon dioxide levels have been higher in the distant past, millions of years ago, when the world was very different than it is today. But never before have such rapid, global-scale changes occurred during the history of human civilization.

Our societies have not been built to withstand the changes that are anticipated in the relatively near future, and thus are not prepared for the effects they are already experiencing: higher temperatures, sea level rise, and other climate change related impacts.

D. Is the globally averaged surface air temperature still increasing? Isn't there recent evidence that it is actually cooling?

Global temperatures are still rising. Climate change is defined as a change in the average conditions over periods of 30 years or more (see FAQ A). On these time scales, global temperature continues to increase. Over shorter time scales, natural variability (due to the effects of El Niño and La Niña events in the Pacific Ocean, for example, or volcanic eruptions or changes in energy from the sun) can reduce the rate of warming or even create a temporary reduction in average surface air temperature. These short-term variations in no way negate the reality of long-term warming. The most recent decade was the warmest since instrumental record keeping began around 1880.

From 1970 to 2010, for example, global temperature trends taken at five-year intervals show both decreases and sharp increases. The five-year period from 2005 to 2010, for example, included a period in which the sun's output was at a low point, oceans took up more than average amounts of heat, and a series of small volcanoes exerted a cooling influence by adding small particles to the atmosphere. These natural factors are thought to have contributed to a recent slowdown in the rate of increase in average surface air temperature caused by the buildup of human-induced greenhouse gases. But while there has been a slowdown in the rate of increase, temperatures are still increasing.

Short-term Variations Versus Long-term Trend

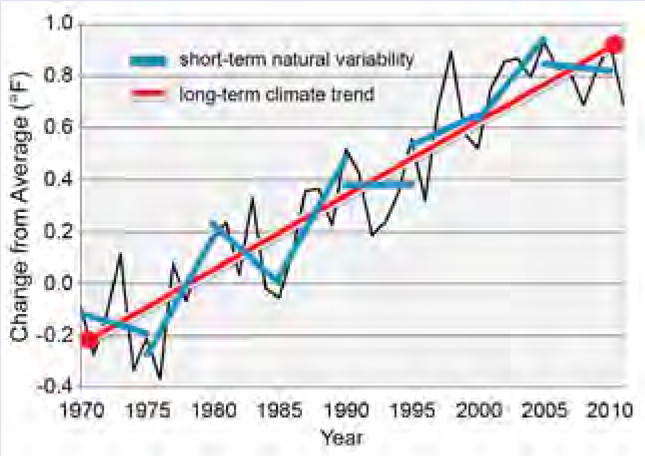


Figure 6. Short-term trends in global temperature (blue lines show temperature trends at five-year intervals from 1970 to 2010) can range from decreases to sharp increases. The evidence of climate change is based on long-term trends over 20-30 years or more (red line). (Data from NOAA NCDC).

In addition, satellite and ocean observations indicate that most of the increased energy in the Earth's climate system from the increasing levels of heat-trapping gases has gone into the oceans. These observations indicate that the Earth-atmosphere climate system has continued to gain heat energy.

In the United States, there has been considerable decade-to-decade variability superimposed on the long-term warming trend. In most seasons and regions, the 1930s were relatively warm and the 1960s/1970s relatively cool. The most recent decade of the 2000s was the warmest on record throughout the United States and globally.

Global Temperature Change: Decade Averages

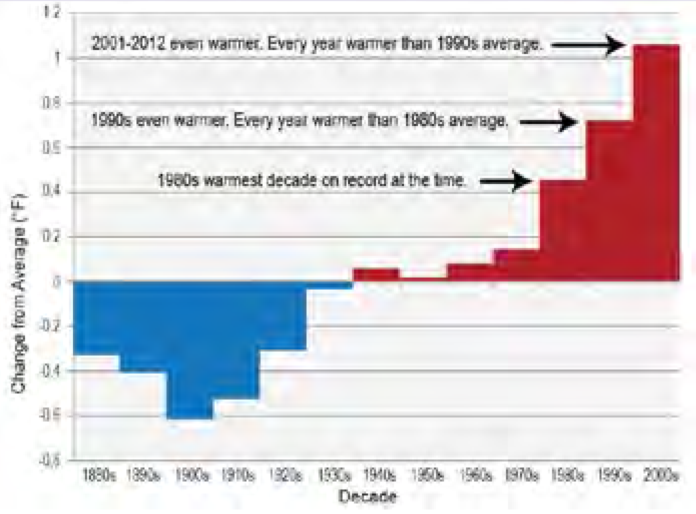


Figure 7. The last five decades have seen a progressive rise in Earth's average surface temperature. Bars show the difference between each decade's average temperature and the overall average for 1901 to 2000. The far right bar includes data for 2001-2012. (Figure source: NOAA NCDC).

E. Is it getting warmer at the same rate everywhere? Will the warming continue?

Temperatures are not increasing at the same rate everywhere, because temperature changes in a given location depend on many factors. However, average global temperatures are projected to continue increasing throughout the remainder of this century due to heat-trapping gas emissions from human activities.

The planet is warming overall (see FAQ I), but some locations could be cooling due to local factors. Temperature changes in a given location are a function of multiple factors, including global and local forces, and both human and natural influences. In some places, including the U.S. Southeast, temperatures actually declined over the last century as a whole (although they have risen in recent decades). Possible causes of the observed lack of warming in the Southeast during the 20th century include increased cloud cover and precipitation,[5] increases in the presence of fine particles called aerosols in the atmosphere (including those produced by burning fossil fuels and by natural sources), expanding forests in the Southeast over this period,[6] decreases in the amount of heat conducted from land to the atmosphere as a result of increases in irrigation,[7] and multi-decadal variability in sea surface temperatures in both the North Atlantic[8] and the tropical Pacific[9] Oceans. At smaller geographic scales, and during certain time intervals, the relative influence of natural variations in climate compared to the human contribution is larger than at the global scale. An observed decrease in temperature at an individual location does not negate the fact that, overall, the planet is warming.

In terms of impacts, "global warming" is probably not the most immediate thing most people would notice. A changing climate affects our lives in many more obvious ways, for example, by increasing the risk of severe weather events such as heat waves, heavy precipitation events, strong hurricanes, and many other aspects of climate discussed throughout this report.

For these reasons, many scientists prefer the term "climate change," which connotes a much larger picture: broad changes in what are considered "normal" conditions. This term encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and other features of the climate system.

At the global scale, some future years will be cooler than the preceding year; some decades could even be cooler than the preceding decade (though that has not happened for more than six decades; see Figure 7). Brief periods of faster temperature increases and also temporary decreases in global temperature can be expected to continue into the future. Nonetheless, each successive decade in the last 30 years has been the warmest in the period of reliable instrumental records (going back to 1850). Based on this historical record and plausible scenarios for future increases in heat-trapping gases, we expect that future global temperatures, averaged over climate timescales of 30 years or more, will be higher than preceding periods as a result of carbon dioxide and other heat-trapping gas emis-

Temperature Trends, 1900-2012

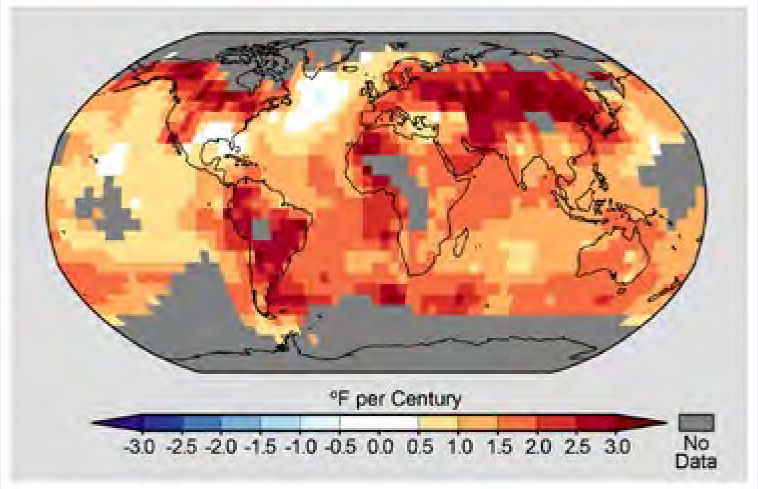


Figure 8. Observed trend in temperature from 1900 to 2012; yellow to red indicates warming, while shades of blue indicate cooling. Gray indicates areas for which there are no data. There are substantial regional variations in trends across the planet, though the overall trend is warming. (Figure source: NOAA NCDC).

Decade-Scale Changes in Average Temperature for U.S. Regions

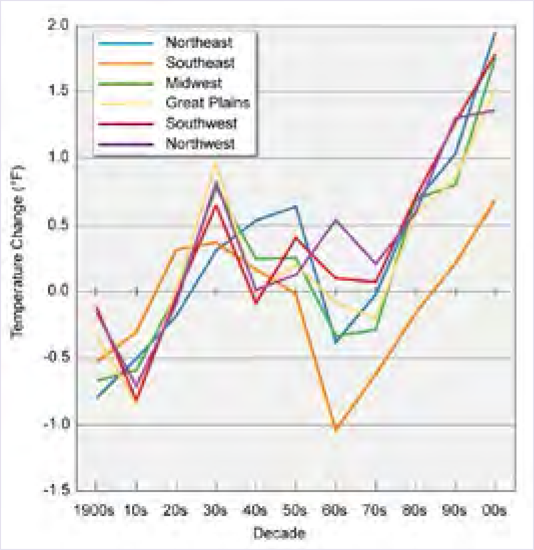


Figure 9. Change in decadal-averaged annual temperature relative to the 1901-1960 average for the six National Climate Assessment regions in the contiguous United States. This figure shows how regional temperatures can be much more variable than global temperatures, going up and down from decade to decade; all regions, however, show warming over the last two decades or more. In the figure, 00s refers to the 12-year period of 2001-2012. (Figure source: NOAA NCDC / CICS-NC).

sions from human activities. A portion of the carbon dioxide emissions from human activities will remain in the atmosphere for hundreds of years and continue to affect the global carbon cycle for thousands of years. Year-to-year projections of regional and local temperatures are more variable than global temperatures, and even at a particular location, future warming becomes increasingly likely over longer periods of time.[1]

F. How long have scientists been investigating human influences on climate?

The scientific basis for understanding how heat-trapping gases affect the Earth's climate dates back to the French scientist Joseph Fourier, who established the existence of the natural greenhouse effect in 1824. The heat-trapping abilities of greenhouse gases were corroborated by Irish scientist John Tyndall with experiments beginning in 1859. Since then, scientists have developed more tools to refine their understanding of human influences on climate, from the invention of the thermometer, to the development of computerized climate models, to the launching of Earth observing satellites that, together, provide global data coverage.

The greenhouse effect is caused by heat-trapping gases, such as water vapor, carbon dioxide, and methane, in the Earth's atmosphere. These gases are virtually transparent to the visible and ultraviolet wavelengths that comprise most of the sun's energy, allowing nearly all of it to reach Earth's surface. However, they are relatively opaque to the heat energy the Earth radiates back outward at infrared wavelengths. Other more abundant gases in the atmosphere like nitrogen and oxygen are largely transparent to the Earth's infrared energy. Greenhouse gases trap some of the Earth's energy inside the atmosphere and prevent it from escaping to space by absorbing and re-emitting that energy in all directions, rather than just upwards. Some of the trapped energy is re-radiated back down to the Earth's surface. This natural trapping effect makes the average temperature of the Earth nearly 60°F warmer than what it would be otherwise. On other planets, like Venus, where there are much higher concentrations of heat-trapping gases in the atmosphere, the greenhouse effect has a much stronger influence on surface temperature, making conditions far too hot for life as we know it.

By the late 1800s, scientists were aware that burning coal, oil, or natural gas produced carbon dioxide, a key heat-trapping gas. They were also aware that methane, another heat-trapping gas, was released during coal mining and other human activities. And they knew that, since the Industrial Revolution, humans were producing increasing amounts of these gases. It was clear that humans were increasing the natural greenhouse effect and that this would warm the planet.

In 1890, Svante Arrhenius, a Swedish chemist, calculated the effect of increasing fossil fuel use on global temperature. This climate model, computed by hand, took two years to complete. Arrhenius' results were remarkably similar to those produced by the most up-to-date global climate models today, although he did not anticipate that atmospheric levels of carbon dioxide would increase as quickly as they have.

In 1938, a British engineer, Guy Callendar, connected rising carbon dioxide levels to the observed increase in the Earth's temperature that had occurred to date. In 1958, Charles David Keeling began to precisely measure atmospheric levels of carbon dioxide in the relatively unpolluted location of Mauna Loa on Hawai'i. Today, those data provide a clear record of the effect of human activities on the chemical composition of the global atmosphere. Many more sources of data corroborate the work of these early pioneers in the field of climate science.

Early Scientists who Established the Scientific Basis for Climate Change

Figure 10. Scientists whose research was key to understanding the greenhouse effect and the impact of human activities on climate.

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

The reason heat-trapping gases like carbon dioxide, methane, and nitrous oxide have such a powerful influence on Earth's climate is their potency: although they are transparent to visible and ultraviolet solar energy, allowing the sun's energy to come in, they are very strong absorbers of the Earth's infrared heat energy, blanketing the Earth and preventing some of the energy to escape to space.

Before the Industrial Revolution, natural levels of carbon dioxide in the atmosphere averaged around 280 parts per million (ppm), that is, 280 molecules of CO_2 per million molecules of air (which is mostly nitrogen and oxygen). In other words, carbon dioxide made up about 0.028% of the volume of the atmosphere. Methane and nitrous oxide, other heat-trapping gases, made up even less, about 700 parts per billion (ppb) and 270 ppb, respectively. Over the last few centuries, emissions from human activities have increased carbon dioxide levels to about 400 ppm, or more than 3,000 billion tons – more than a 40% increase. Over the same time period, methane and nitrous oxide levels in the atmosphere have risen to around 1800 ppb and 320 ppb, respectively.

As the concentrations in the atmosphere of these heat-trapping gases increase due to human activities, they are absorbing greater and greater amounts of infrared heat energy emitted from the Earth's surface. As discussed in FAQ F, the gases then re-radiate some of this heat back to the surface, effectively trapping the heat inside the Earth's climate system and warming the Earth's surface.

These heat-trapping gases do not absorb energy equally across the infrared spectrum. Carbon dioxide absorption is very strong at certain wavelengths of infrared radiation, whereas water vapor absorbs more broadly across most of the spectrum. Water vapor is the most important naturally occurring heat-trapping greenhouse gas, but small increases in heat energy absorption by carbon dioxide and other heat-trapping gases trigger increases in water vapor that amplify the infrared trapping, leading to further warming. As a result, water vapor is considered a "feedback" rather than a direct forcing on climate.

Human Influence on the Greenhouse Effect

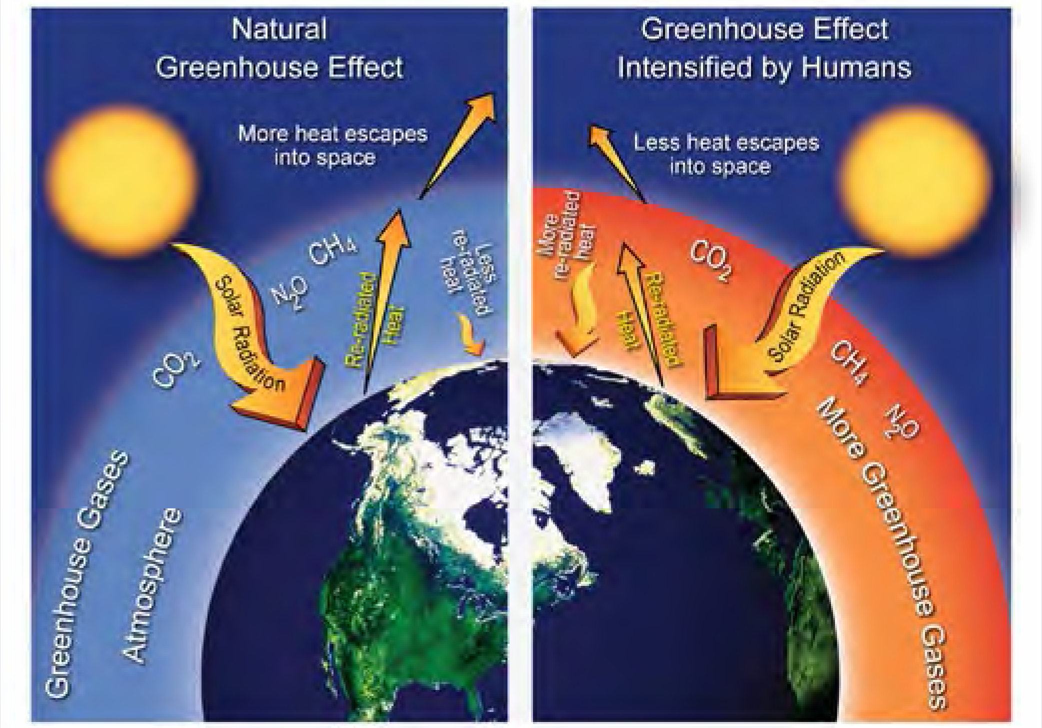


Figure 11. (left) A stylized representation of the natural greenhouse effect. Most of the sun's radiation reaches the Earth's surface. Naturally occurring heat-trapping gases, including water vapor, carbon dioxide, methane, and nitrous oxide, do not absorb the short-wave energy from the sun but do absorb the long-wave energy re-radiated from the Earth, keeping the planet much warmer than it would be otherwise. (right) In this stylized representation of the human-intensified greenhouse effect, human activities, predominantly the burning of fossil fuels (coal, oil, and gas), are increasing levels of carbon dioxide and other heat-trapping gases, increasing the natural greenhouse effect and thus Earth's temperature. (Figure source: modified from National Park Service[10]).

H. Could the sun or other natural factors explain the observed warming of the past 50 years?

No. Since accurate satellite-based measurements of solar output began in 1978, the amount of the sun's energy reaching Earth has slightly decreased, which should, on its own, result in slightly lower temperatures; but the Earth's temperature has continued to rise. The sun can explain less than 10% of the increase in temperature since 1750, and none of the increase in temperature since 1960.

Patterns of vertical temperature change (from the Earth's surface to the upper atmosphere) provide further evidence that the sun cannot be responsible for the observed changes in climate. An increase in solar output would warm the atmosphere consistently from top to bottom. Warming from increasing heat-trapping gases, on the other hand, should be concentrated in the lower atmosphere (troposphere), while the upper atmosphere (stratosphere) would cool. Satellite measurements and weather balloon records reveal that the troposphere has warmed, and the stratosphere has cooled. This observed pattern of vertical temperature change matches what we would expect from the increase in heat-trapping gases, not an increase in solar output.

Changes in the sun's magnetic field are known to affect the intensity of cosmic rays reaching Earth's atmosphere and there is some suggestion that this could affect cloud formation; however, observations indicate that the magnitude of this effect is much smaller than the effects from the human-related changes in heat-trapping gases and from particle emissions on clouds and the changes in climate.

Large explosive volcanic eruptions can cool climate for a few years after an eruption, if the eruption is powerful enough to send particles far up into the atmosphere. In the atmosphere, sulfur dioxide from volcanoes is converted into sulfuric acid particles that can scatter sunlight, cooling the Earth's surface. Particles from exceptionally large eruptions like Mount Pinatubo in 1991 or Krakatoa in 1883 can reach all the way into the stratosphere, where they can stay for several years. Eventually, they fall back into the troposphere where they are rapidly removed by precipitation. Volcanoes also emit carbon dioxide, but this amount is less than 1% annually of the emissions occurring from human activities.

Thus, natural factors cannot explain recent warming. In fact, observed solar and volcanic activity would have tended to slightly cool the Earth, and other natural variations are too small to account for the amount of warming over the last 50 years.

Measurements of Surface Temperature and Sun's Energy

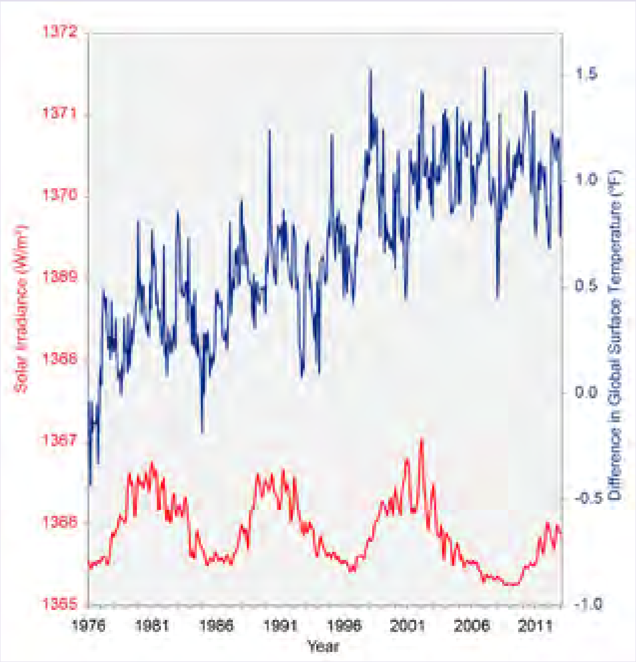


Figure 12. Changes in the global surface temperature (top) and the solar flux (bottom) since 1900 (temperatures are relative to 1961-1990). The temperatures are based on thermometer observations of the Earth's surface temperature, while the solar flux at the top of Earth's atmosphere is based on satellite observations starting in 1978 and on proxy observations before then. (Figure source: NOAA NCDC / CICS-NC).

I. How do we know that human activities are the primary cause of recent climate change?

Many lines of evidence demonstrate that human activities are primarily responsible for recent climate changes. First, basic physics dictates that increasing the concentration of CO_2 and other heat-trapping gases in the atmosphere will cause the climate to warm. Second, modeling studies show that when human influences are removed from the equation, climate would actually have cooled slightly over the past half century. And third, the pattern of warming through the layers of atmosphere demonstrates that human-induced heat-trapping gases are responsible, rather than some natural change.

Scientists are continually designing experiments to test whether observed climate changes are unusual and then to determine their causes. This field of study is known as "detection and attribution." Detection involves looking for evidence of changes or trends. Attribution attempts to identify the causes of these changes from a line-up of "suspects" that include changes in energy from the sun, powerful volcanic eruptions – and today, human-induced emissions of heat-trapping gases.

Detection and attribution analyses have confirmed that recent changes cannot have been caused either by internal climate system variations or by solar and volcanic influences (see FAQs C and H). Human influences on the climate system – including heat-trapping gas emissions, atmospheric particulates, and land-use and land-cover change – are required to explain recent changes (see Figure 14).

Detection and attribution has been used to analyze the contribution of human influences to changes in global average conditions, in extreme events, and even in the change in risk of specific types of events, such as the 2003 European heat wave. Such analyses have found that it is virtually certain that observed changes in many aspects of the climate system are the result of influences of human activities. Scientific analyses also provide extensive evidence that the likelihood of some types of extreme events (such as heavy rains and heat waves) is now significantly higher due to human-induced climate change.

Human Influences Apparent in Many Aspects of the Changing Climate

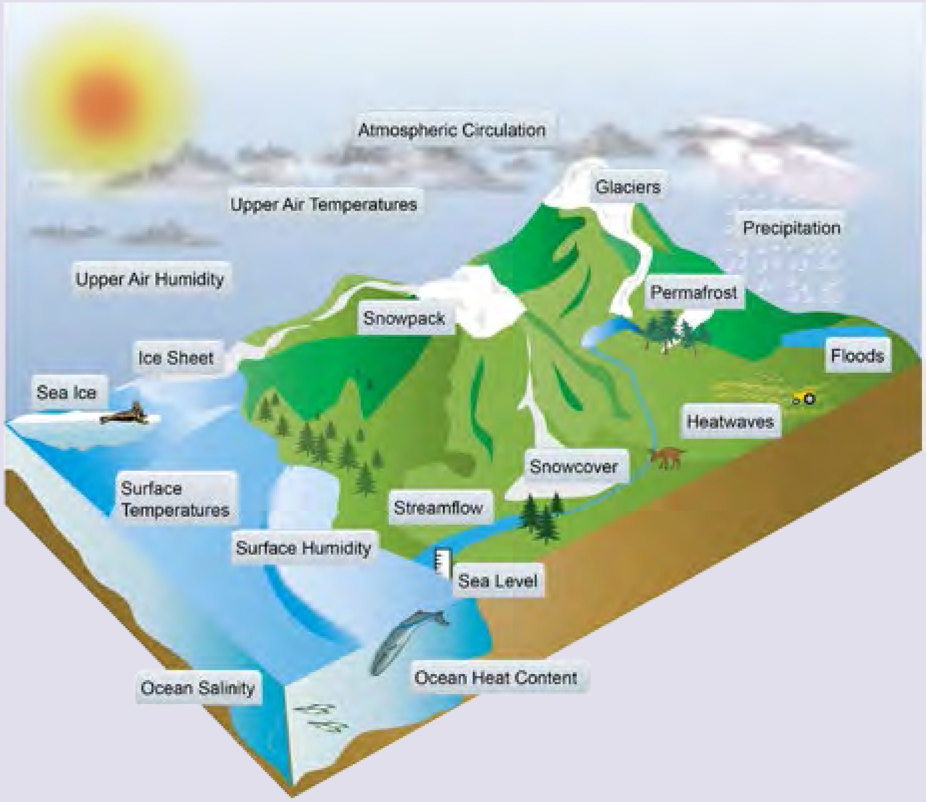


Figure 13. Figure shows examples of the many aspects of the climate system in which changes have been formally attributed to human emissions of heat-trapping gases and particles by studies published in peer-reviewed science literature. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be explained without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the dominant contributor to recently observed climate changes. (Figure source: NOAA NCDC).

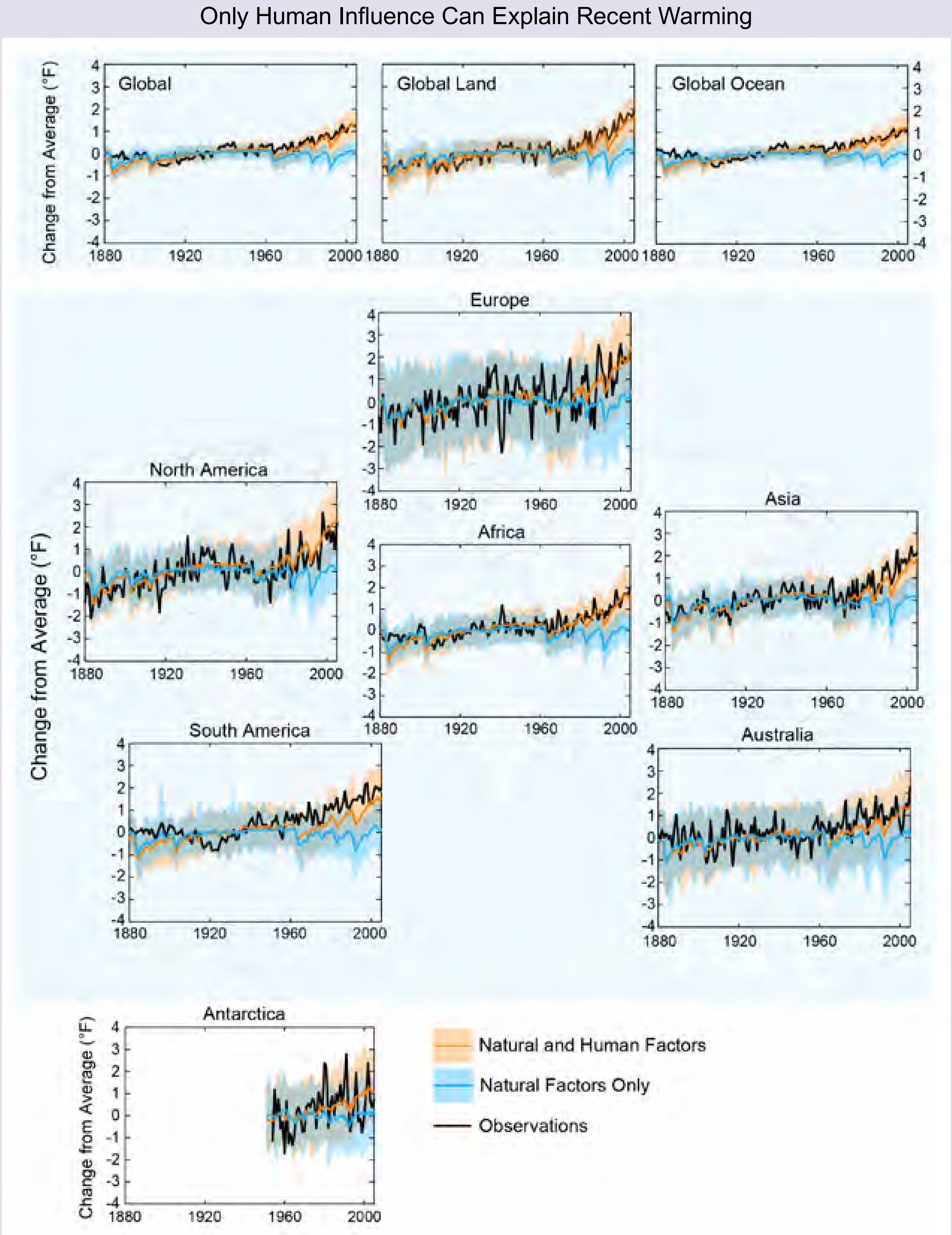


Figure 14. Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the annually averaged observed changes. The blue shading represents estimates from a broad range of climate simulations including solely natural (solar and volcanic) changes in forcing. The orange shading is from climate model simulations that include the effects of both natural and human contributions. These analyses demonstrate that the observed changes, both globally and on a continent-by-continent basis, are caused by the influence of human activities on climate. (Figure source: updated from Jones et al. 2013[11]).

J. What is and is not debated among climate scientists about climate change?

Multiple analyses of the peer-reviewed science literature have repeatedly shown that more than 97% of scientists in this field agree that the world is unequivocally warming and that human activity is the primary cause of the warming experienced over the past 50 years. Spirited debates on some details of climate science continue, but these fundamental conclusions are not in dispute.

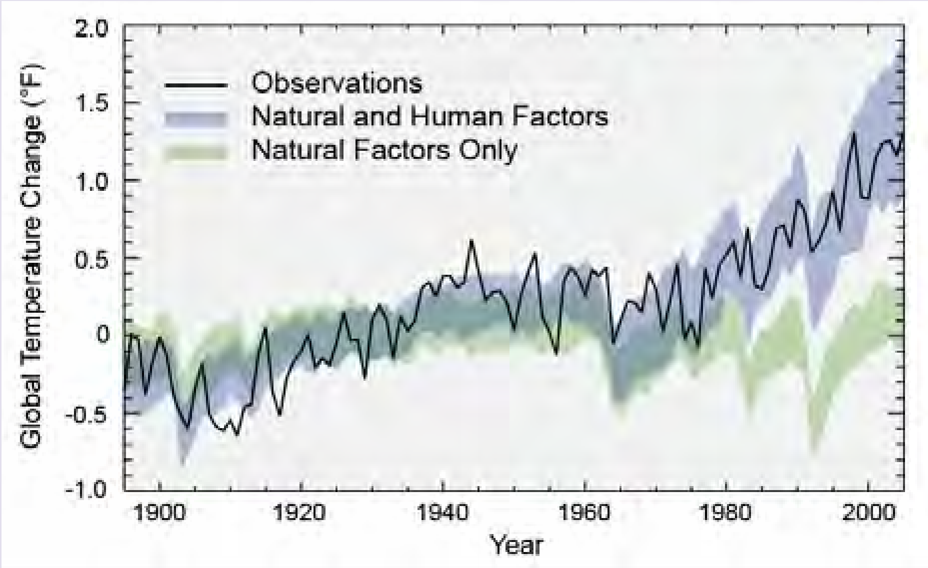
The scientific method is built on scrutiny and debate among scientists. Scientists are rigorously trained to conduct experiments to test a question, or hypothesis, and submit their findings to the scrutiny of other experts in their field. Part of that scrutiny, known as "peer review," includes independent scientists examining the data, analysis methods, and findings of a study that has been submitted for publication. This peer review process provides quality assurance for scientific results, ensuring that anything published in a scientific journal has been reviewed and approved by other independent experts in the field and that the authors of the original study have adequately responded to any criticisms or questions they received.

However, peer review is only the first step in the long process of acceptance of new ideas. After publication, other scientists will often undertake new studies that may support or reject the findings of the original study. Only after an exhaustive series of studies over many years, by many different research groups, are new ideas widely accepted.

Given that new scientific understanding emerges from this exhaustive process, the widespread agreement in the scientific community regarding the reality of climate change and the leading role of human activities in driving this change is striking. This consensus includes agreement on the fundamental scientific principles that underlie this phenomenon, as well as the weight of empirical evidence that has been accumulated over decades, and even centuries, of research (see FAQ F).

The conclusion that the world is warming, and that this is primarily due to human activity, is based on multiple lines of evidence, from basic physics to the patterns of change through the climate system (including the atmosphere, oceans, land, biosphere, and cryosphere). The warming of global climate and its causes are not matters of opinion; they are matters of scientific evidence, and that evidence is clear. Scientists do not "believe" in human-induced climate change; rather, the widespread agreement among scientists is based on the vast array of evidence that has accumulated over the last 200 years. When all of the evidence is considered, the conclusions are clear.

There is more work to be done to fully understand the many complex and interacting aspects of climate change, and important questions remain. Scientific debate continues on questions such as: Exactly how sensitive is the Earth's climate to human emissions of heat-trapping gases? How will climate change affect clouds? How will climate change affect snowstorms in Chicago, tornadoes in Oklahoma, and droughts in California? How do particle and soot emissions affect clouds? How will climate change be affected by changes in clouds and the oceans? These detailed questions, and more, serve as healthy indicators that the scientific method is alive and well in the field of climate science. But the fact that climate is changing, that this is primarily in response to human activities, and that climate will continue to change in response to these activities, is not in dispute (see FAQ I).



Separating Human and Natural Influences on Climate

Figure 15. The green band shows how global average temperature would have changed due to natural forces only, as simulated by climate models. The blue band shows model simulations of the effects of human and natural factors combined. The black line shows observed global average temperatures. As indicated by the green band, without human influences, temperature over the past century would actually have cooled slightly over recent decades. The match up of the blue band and the black line illustrate that only the inclusion of human factors can explain the recent warming. (Figure source: adapted from Huber and Knutti, 2012[12]).

K. Is the global surface temperature record good enough to determine whether climate is changing?

Yes. There have been a number of studies that have examined the U.S. and global temperature records in great detail. These have used a variety of methods to study the effects of changes in instruments, time of observations, station siting, and other potential sources of error. All studies reinforce high confidence in the reality of the observed upward trends in temperature.

Global surface temperatures are measured by weather stations over land and by ships and buoys over the ocean. These records extend back regionally for over 300 years in some locations and near-globally to the late 1800s.

Scientists have undertaken painstaking efforts to obtain, digitize, and collate these records. Because of the way these measurements have been taken, many of the records contain results that are skewed by, for example, a change of instrument or a station move. It is essential to carefully examine the data to identify and adjust for such effects before the data can be used to evaluate climate trends.

A number of different research teams have taken up this challenge. Some have spent decades carefully analyzing the data and continually reassessing their approaches and refining their records. These independently produced estimates are in very good agreement at both global and regional scales.

Scientists have also considered other influences that could contaminate temperature records. For example, many thermometers are located in urban areas that could have warmed over time due to the urban heat island effect (in which heat absorbed by buildings and asphalt makes cities warmer than the surrounding countryside). At least three different research teams have examined how this might affect U.S. temperature trends. All have found that this effect is adequately accounted for by the data corrections. At the global scale, if all of the urban stations are removed from the global temperature record, the evidence of warming over the past 50 years remains intact. Other studies have shown that the temperature *trends* of rural and urban areas in close proximity essentially match, even though the urban areas may have higher temperatures overall.

Observed Change in Global Average Temperature

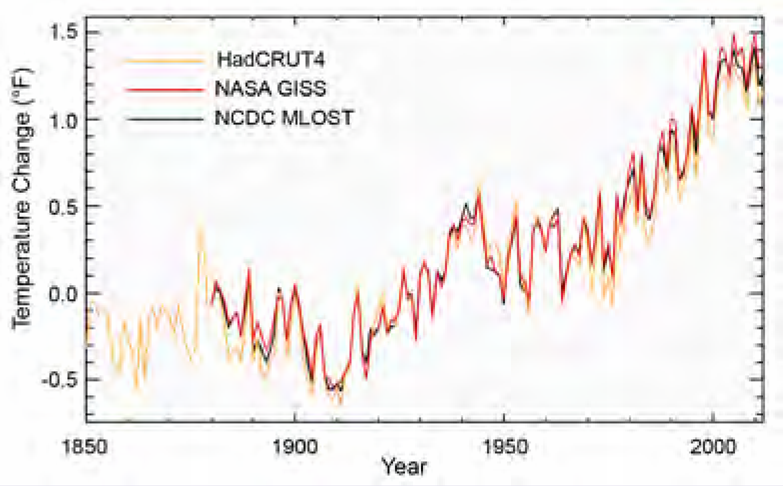


Figure 16. Three different global surface temperature records all show increasing trends over the last century. The lines show annual differences in temperature relative to the 1901-1960 average. Differences among data sets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Figure source: NOAA NCDC / CICS-NC).

L. Is Antarctica gaining or losing ice? What about Greenland?

The ice sheets on both Greenland and Antarctica, the largest areas of land-based ice on the planet, are losing ice as the atmosphere and oceans warm. This ice loss is important both as evidence that the planet is warming, and because it contributes to rising sea levels.

One way that scientists are evaluating ice loss is by observing changes in the gravitational fields over Greenland and Antarctica. Fluctuations in the pull of gravity over these major ice sheets reflect the loss of ice over time. Over the last decade, the GRACE (Gravity Recovery and Climate Experiment) satellites have measured changes in the gravitational pull of the continents and revealed that, on the whole, both Greenland and Antarctica are losing ice. It is clear that these ice sheets are already losing mass as a result of human-induced climate change, and the evidence suggests that Greenland and Antarctica are likely to continue to lose ice mass for centuries. How rapidly the Greenland and Antarctic Ice Sheets will melt as warming continues represents the largest uncertainty in projections of future sea level rise.

Paleoclimate records show that the giant ice sheets of Greenland and Antarctica (as well as others, such as the Laurentide Ice Sheet that covered much of North America during the last glacial maximum) have expanded and contracted as the Earth cooled or warmed in the past. As temperature increases and precipitation patterns shift in response to human-induced climate change, scientists expect the ice sheets of Greenland and

Ice Loss from the Two Polar Ice Sheets

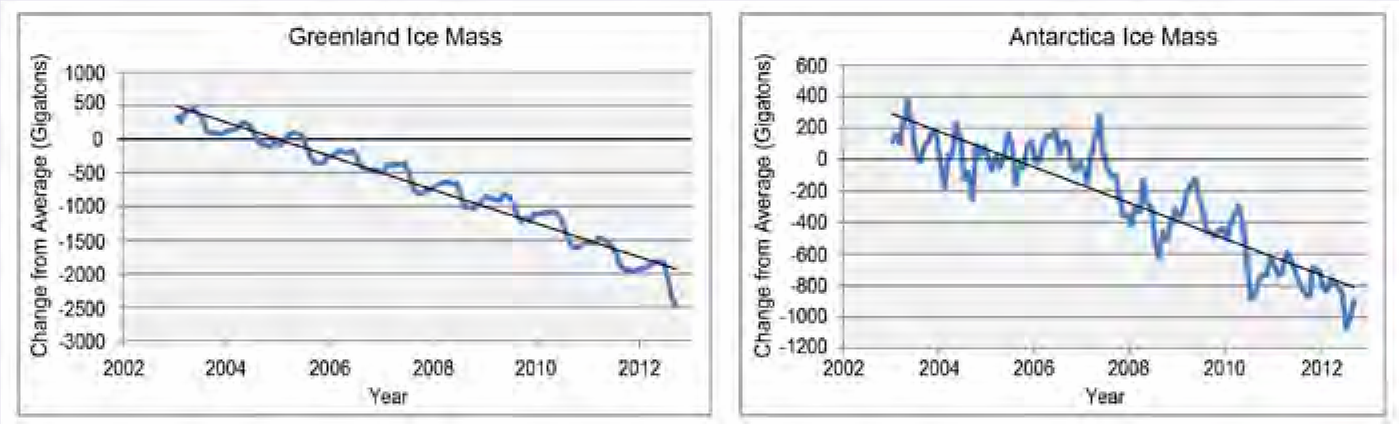


Figure 17. GRACE (Gravity Recovery and Climate Experiment) satellite measurements show that both Greenland and Antarctica are, on the whole, losing ice as the atmosphere and oceans warm. (Figure source: adapted from Wouters et al. 2013[13]).

Antarctica to continue responding in a similar way. Over time horizons of hundreds to thousands of years, a general melting and reduction in the extent of both of these ice sheets is expected to occur in response to global warming. Over shorter time frames of years to decades, however, the response of these ice sheets is more complicated.

The Antarctic Ice Sheet is up to three miles deep and contains enough water to raise sea level about 200 feet. Because Antarctica is so cold, there is little melt of the ice sheet in the summer. However, the ice on the continent slowly flows down the mountains and through the valleys toward the ocean. Some parts of the ice sheet extend out into the ocean as "ice shelves." Here, above-freezing ocean water speeds up the process called "calving" that breaks the ice into free floating icebergs. Melting and calving and the flow of ice into the oceans around Antarctica has accelerated in recent decades and is now contributing about 0.005 to 0.010 inches per year to sea level rise. It is possible that the West Antarctic Ice Sheet, which contains enough ice to raise global sea levels by 10 feet, could begin to lose ice much more quickly if ice shelves in the region begin to disintegrate at the edges.

Greenland contains only about one tenth as much ice as the Antarctic Ice Sheet, but if Greenland's ice were to entirely melt, global sea level would rise 23 feet. Greenland is warmer than Antarctica, so unlike Antarctica, melting occurs over large parts of the surface of Greenland's ice sheet each summer. Greenland's melt area has increased over the past several decades. Satellite measurements indicate that the Greenland Ice Sheet is presently thinning at the edges (especially in the south) and slowly thickening in the interior, increasing the steepness of the ice sheet, which causes the ice to flow toward the ocean. Several of the major outlet glaciers that drain the Greenland Ice Sheet have sped up in the past decade. Recent scientific studies suggest that warming of the ocean at the edges of the outlet glaciers may contribute to this speed-up. Greenland's ice loss has increased substantially in the past decade or two, and is now contributing 0.01 to 0.02 inches per year to sea level rise (about twice the rate of Antarctica's mass loss). This increased rate of ice loss means that Greenland's contribution to global sea level rise is now similar to the effect from smaller glaciers worldwide and from Antarctica.

M. Weren't there predictions of global cooling in the 1970s?

No. An enduring myth about climate science is that in the 1970s the climate science community supposedly predicted "global cooling" and an "imminent" ice age. A review of the scientific literature shows that this was not the case. On the contrary, even then, discussions of human-related warming dominated scientific publications on climate and human influences.

Where did all the discussion about global cooling come from? First, temperature records from about 1940 to 1970 showed a slight global cooling trend, intensified by temporary increases in snow and ice cover across the Northern Hemisphere. Short-term natural variations in the Earth's climate (see FAQ A) and increasing emissions of sulfur and other particles from coal-burning power plants, which reflect solar energy and have a net cooling effect on the Earth, likely contributed to cooler temperatures during that time period. Several unusually severe winters in Asia and parts of North America in the 1970s raised people's concerns about cold weather. The popular press, including *Time*, *Newsweek*, and *The New York Times*, carried a number of articles about cooling at that time.

Second, climate scientists study both natural and human-induced changes in climate. Over the last century, scientists have learned a great deal about what drives Earth's ice ages. Scientific understanding of what are called the Milankovitch cycles (cyclical changes in the Earth's orbit that can explain the onset and ending of ice ages) led a few scientists in the 1970s to suggest that the current warm interglacial period might be ending soon, plunging the Earth into a new ice age over the next few centuries. Scientists continue to study this issue today; the latest information suggests that, if the Earth's climate were being controlled primarily by natural factors, the next cooling cycle would begin sometime in the next 1,500 years. However, humans have so altered the composition of the atmosphere that the next glaciation has now been delayed.

Published Climate Change Research Papers

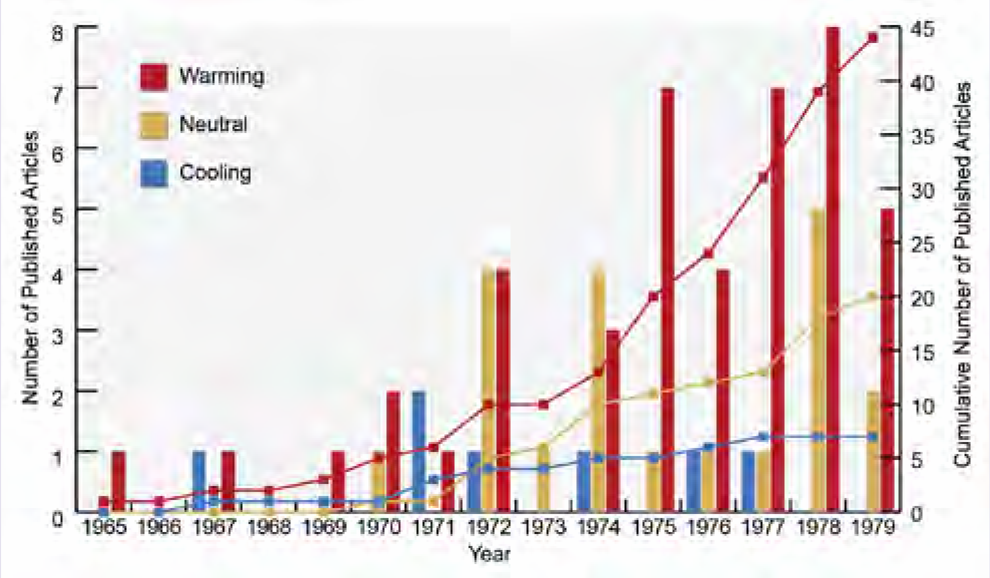


Figure 18. The number of papers classified as predicting, implying, or providing supporting evidence for future global cooling, warming, and neutral categories. Bars indicate number of articles published per year. Squares indicate cumulative number of articles published. For the period 1965 through 1979, the literature survey found seven papers suggesting further cooling, 20 neutral, and 44 warming. Even in the early years of the study of climate change, more science studies were discussing concerns about global warming than global cooling. (Figure source: Peterson et al. 2008[14]).

N. How is climate projected to change in the future?

Climate is projected to continue to warm, with the amount of future warming ranging from another 3°F to another 12°F by 2100, depending primarily on the level of emissions from human activities, principally the burning of fossil fuels. For precipitation, wet areas are generally projected to get wetter while dry areas get drier. More precipitation is expected to fall in heavy downpours. Natural variability will still play a role in year-to-year changes.

Future climate cannot be "predicted" because human activities are currently the most important driver of climate change and we cannot predict what society will choose to do with regard to emissions. Rather, we can *project* the climate change that would result from a given set of assumptions, or future scenarios, regarding human activities (including changes in population, technology, economics, energy, and policy). Future changes also have some uncertainty due to natural variability, particularly over shorter time scales (see FAQ A) and limitations in scientific understanding of exactly how the climate system will respond to human activities (see FAQ S).

The relative importance of these three sources of uncertainty changes over time. Which type of uncertainty is most important also depends on what type of change is being projected: whether, for example, it is for average conditions or extremes, or for temperature or precipitation trends (see FAQ S).

Over the next few decades, global average temperature over 30-year climate timescales is expected to continue to increase (see FAQ D), while natural variability still plays a significant role in year-to-year changes (see FAQ A). The amount of climate change expected over this time period is unlikely to be significantly altered by reducing current heat-trapping gas emissions alone or even by stabilizing atmospheric levels of carbon dioxide and other gases. This is because near-term warming will be caused primarily by emissions that have already occurred, due to the lag in the temperature response to changes in atmospheric composition. This lag is primarily the result of the very large heat storage capacity of the world's oceans and the length of time required for that heat to be transferred to the deep ocean. At smaller geographical scales, temperatures are projected to increase in most regions in the next few decades, but a few regions could experience flat or even decreasing temperatures. Any climate change always represents the net effect of multiple global and local factors, both human-related and natural (see FAQ E).

Beyond the middle of this century, global and regional temperature changes will be determined primarily by the rate and amount of various emissions released by human activities, as well as by the response of the Earth's climate system to those emissions. Efforts to rapidly and significantly reduce emissions of heat-trapping gases can still limit the global temperature increase to 3.6°F (2°C) relative to the 1901-1960 time period. However, significantly greater temperature increases are expected if emissions follow higher scenarios associated with continuing growth in the use of fossil fuels; in that case, the increase in U.S. average air temperature is likely to exceed 11°F by the end of this century. This amount of temperature increase would reshape human societies in ways that are almost unthinkable to us today.

Precipitation patterns are also expected to continue to change throughout this century and beyond. In general, wet areas are projected to get wetter and dry areas, drier. In some areas, located in between wetter and drier areas, the total amount of precipitation falling over the course of a year is not expected to significantly change. Following the observed trends over recent decades, more precipitation is expected to fall as heavier precipitation events. In many mid-latitude regions, including the United States, there will be fewer days with precipitation but the wettest days will be wetter. Large-scale shifts towards wetter or drier conditions and the projected increases in heavy precipitation are expected to be greater under higher emissions scenarios as compared to lower ones.

Observed and Projected U.S. Temperature Change

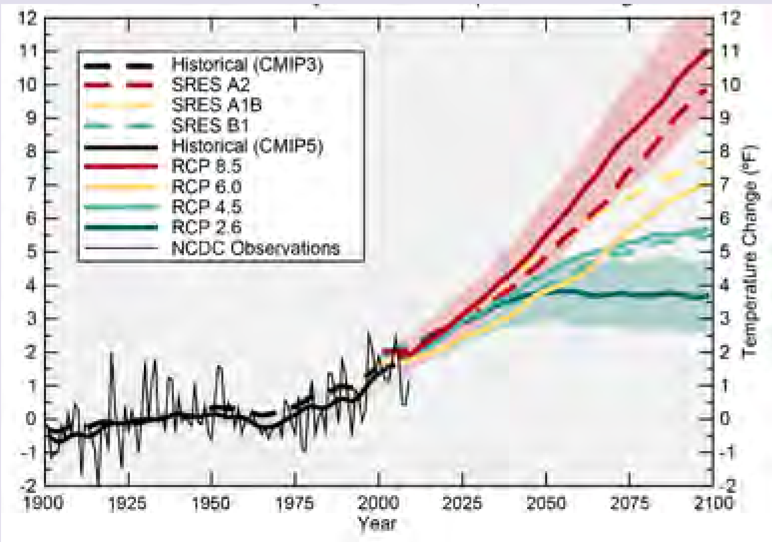


Figure 19. Projected average annual temperature changes over the contiguous United States for multiple future scenarios relative to the 1901-1960 average temperature. The dashed lines are results from the previous generation of climate models and scenarios, while solid lines show the most recent generation of climate model simulations and scenarios. Changes in temperature over the U.S. are expected to be higher than the change in global average temperatures (Figure 23). Differences in these projections are principally a result of differences in the scenarios. (Data from CMIP3, CMIP5, and NOAA NCDC).

O. Does climate change affect severe weather?

Yes, climate change can and has altered the risk of certain types of extreme weather events. The harmful effects of severe weather raise concerns about how the risk of such events might be altered by climate change. An unusually warm month, a major flood or a drought, a series of intense rainstorms, an active tornado season, landfall of a major hurricane, a big snowstorm, or an unusually severe winter inevitably lead to questions about possible connections to climate change.

For example, more extreme high temperatures and fewer extreme cold temperatures occur in a warmer climate (although extreme cold events can and do still occur – just less frequently). In the United States, more than twice as many high temperature records as compared to low temperature records were broken in the period of 2001-2012.

Also, in many areas, heavy rainfall events have already, and will continue to become more frequent and severe as climate continues to change. The intensity and rainfall rates of Atlantic hurricanes are projected to increase, with the strongest storms getting stronger. Recent research has shown how climate change can alter atmospheric circulation and weather patterns such as the jet stream, affecting the location, frequency, and duration of these and other extremes. While there have always been extreme events due to natural causes, scientific evidence indicates that the probability and severity of some types of events has increased due to climate change.

For other types of extreme weather events important to the United States, such as tornadoes and severe thunderstorms, more research is needed to understand how climate change will affect them. These events occur over much smaller scales, which makes observations and modeling more challenging. Projecting the future influence of climate change on these events can also be complicated by the fact that some of the risk factors for these events may increase with climate change, while others may decrease.

P. How are the oceans affected by climate change?

The oceans cover more than two-thirds of the Earth's surface and play a very important role in regulating the Earth's climate and in climate change. Today, the world's oceans absorb more than 90% of the heat trapped by increasing levels of carbon dioxide and other greenhouse gases in the atmosphere due to human activities. This extra energy warms the ocean, causing it to expand. This in turn causes sea level to rise. Of the global rise in sea level observed over the last 35 years, about 40% is due to this warming of the water. Most of the rest is due to the melting of glaciers and ice sheets. Ocean levels are projected to rise another 1 to 4 feet over this century, with the precise number largely depending on the amount of global temperature rise and polar ice sheet melt.

Observations from past climate combined with climate model projections of the future suggest that over the next 100 years the Atlantic Ocean's overturning circulation (known as the "Ocean Conveyor Belt") could slow down as a result of climate change. These ocean currents carry warm water northward across the equator in the Atlantic Ocean, warming the North Atlantic (and Europe) and cooling the South Atlantic. A slowdown of the Conveyor Belt would increase regional sea level rise along the east coast of the United States and change patterns of temperature in Europe and rainfall in Africa and the Americas, but would not lead to global cooling.

Warming ocean waters also affect marine ecosystems like coral reefs, which can be very sensitive to temperature changes. When water temperatures become too high, coral expel the algae (called zooxanthellae) which help nourish them and give them their vibrant color. This is known as coral bleaching. If the high temperatures persist, the coral die.

In addition to the warming, the acidity of seawater is increasing as a direct result of increasing atmospheric carbon dioxide (see FAQ Q). The oceans are now absorbing about a quarter of the carbon dioxide produced by human activities every year. The dissolved carbon dioxide reacts with seawater to form carbonic acid, which makes the water more acidic, making it more difficult for shellfish, corals, and other living things to grow their shells or skeletons. Both the increased acidity and higher temperature of the oceans are expected to negatively affect corals and other living things over the coming decades and beyond.

Coral Bleaching

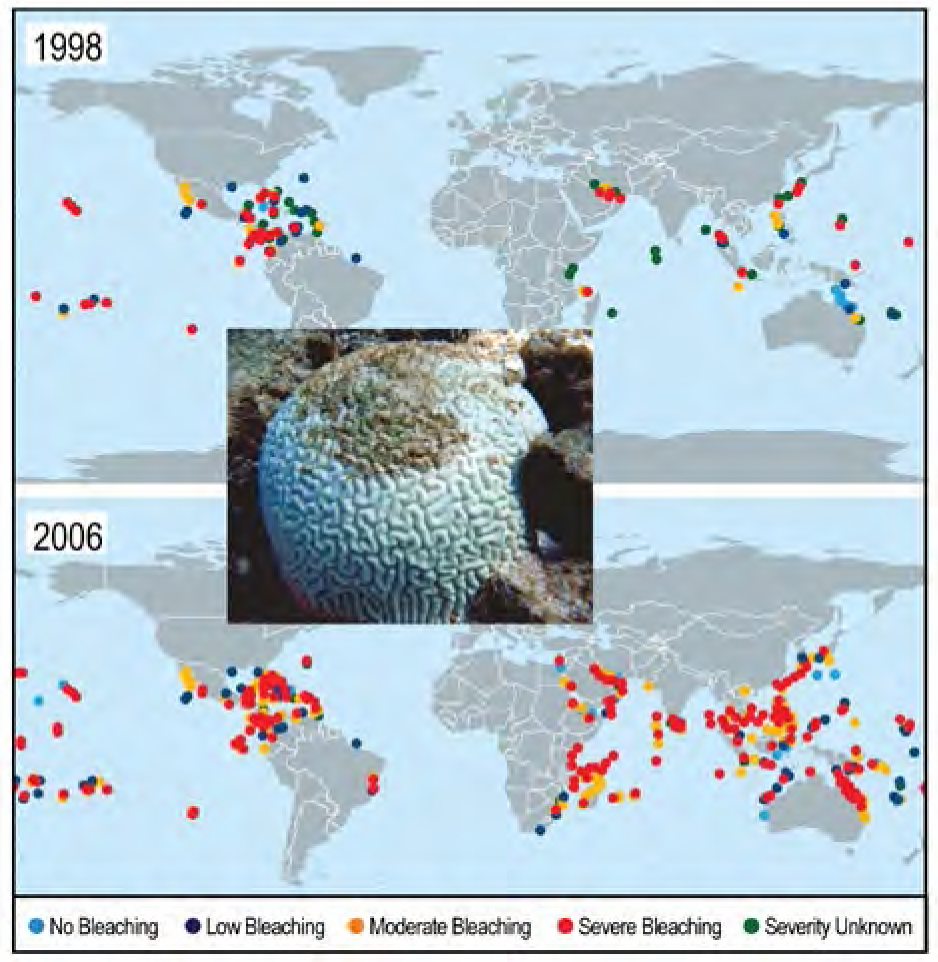


Figure 20. (Photo) Bleached brain coral; (Maps) The global extent and severity of mass coral bleaching have increased worldwide over the last decade. Red dots indicate severe bleaching. (Figure source: Marshall and Schuttenberg 2006;[15] Photo credit: NOAA).

Q. What is ocean acidification?

As human-induced emissions of carbon dioxide build up in the atmosphere, excess carbon dioxide dissolves into the oceans, where it reacts with seawater to form carbonic acid, which makes ocean waters more acidic and corrosive. These changes to ocean chemistry can affect many living things, and possibly the entire food web.

Dissolved calcium and carbonate ions are the building blocks for the skeletons and shells of many living things in the oceans. Ocean acidification lowers the availability of carbonate ions in many parts of the ocean, affecting the ability of some marine life to produce and maintain their shells.

Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units, representing approximately a 30% increase in acidity. The oceans will continue to absorb carbon dioxide produced by human activities and become even more acidic in the future. Projections of carbon dioxide levels indicate that by the end of this century the surface waters of the ocean could be as much as 150% more acidic, resulting in a pH that the oceans have not experienced for more than 20 million years and effectively transforming marine life as we know it.

Ocean acidification is expected to affect ocean species to varying degrees. Some photosynthetic algae and seagrass species may benefit from higher CO_2 conditions in the ocean, as they require CO_2 to live, as do plants on land. On the other hand, studies have shown that a more acidic environment has dramatic negative effects on some calcifying species, including pteropods, oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. When shelled species are at risk, the entire food web may also be at risk.

Ocean Acidification and the Food Web

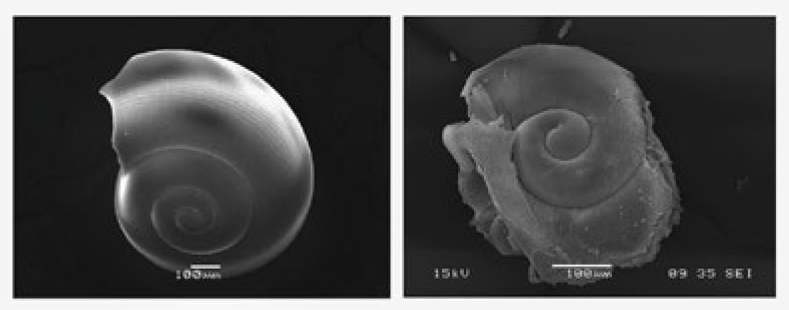


Figure 21. Pteropods, or “sea butterflies,” are sea creatures about the size of a small pea. Pteropods are eaten by organisms ranging in size from tiny krill to whales, and are an important source of food for North Pacific juvenile salmon. The photos above show what happens to a pteropod’s shell when it encounters seawater that is too acidic. The left panel shows a shell collected from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod collected in a region with higher acidity (Photo credits: (left) Bednaršek et al. 2012;[16] (right) Nina Bednaršek).

R. How reliable are the computer models of the Earth’s climate?

Climate models are used to analyze past changes in the long-term averages and variations in temperature, precipitation, and other climate indicators, and to make projections of how these trends may change in the future. Today’s climate models do a good job at reproducing the broad features of the present climate and changes in climate, including the significant warming that has occurred over the last 50 years. Hence, climate models can be useful tools for testing the effects of changes in the factors that drive changes in climate, including heat-trapping gases, particulates from human and volcanic sources, and solar variability.

Scientists have amassed a vast body of knowledge regarding the physical world. Unlike many areas of science, however, scientists who study the Earth’s climate cannot build a “control Earth” and conduct experiments on this Earth in a lab. To experiment with the Earth, scientists instead use this accumulated knowledge to build climate models, or “virtual Earths.” In studying climate change, these virtual Earths serve as an important way to integrate different kinds of knowledge of how the climate system works. These models can be used to test scientific understanding of the response of the Earth’s climate to past changes (such as the transition from the last glacial maximum to our current warm interglacial period) as well as to develop projections of future changes (such as the response of the Earth’s climate to human activities).

Climate models are based on mathematical and physical equations representing the fundamental laws of nature and the many processes that affect the Earth’s climate system. When the atmosphere, land, and ocean are divided up into small grid cells and these equations are applied to each grid cell, the models can capture the evolving patterns of atmospheric pressures, winds, temperatures, and precipitation. Over longer timeframes, these models simulate wind patterns, high and low pressure systems, and other weather characteristics that make up climate.

Some important physical processes are represented by approximate relationships because the processes are not fully understood, or they are at a scale that a model cannot directly represent. Examples include clouds, convection, and turbulent mixing of the atmosphere, for which important processes are much smaller than the resolution of current models. These approximations lead to uncertainties in model simulations of climate.

Climate models require enormous computing resources, especially to capture the geographical details of climate. Today's most powerful supercomputers are enabling climate scientists to more thoroughly examine effects of climate change in ways that were impossible just five years ago. Over the next decade, computer speeds are predicted to increase another 100 fold or more, permitting even more details of the climate system to be explored.

Climate Models and Temperature Change

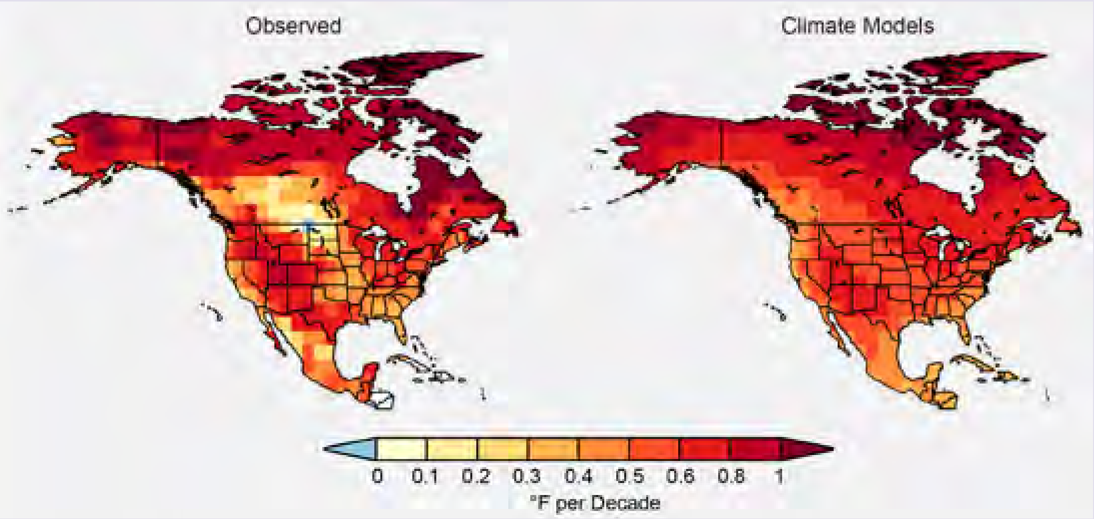


Figure 22. The large-scale geographical patterns and approximate magnitude of the surface air temperature trend from 1980 to 2005 from observational data (left) is approximately captured by computer models of the climate system (right). The pattern from the computer models is an average based on 43 different global climate models (CMIP5) used in the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report. The observations are a combination of both the human contribution to recent warming as well as the natural temperature variations. Averaging these model simulations suppresses the natural variations and thus shows mainly the human contribution, which is the reason that the smaller-scale details are different between the two maps. (Figure source: NOAA NCDC / CICS-NC).

S. What are the key uncertainties about climate change?

Available evidence gives scientists confidence that humans are having a significant effect on climate and will continue to do so over this century and beyond. In particular, continued use of fossil fuels and resulting emissions will significantly alter climate and lead to a much warmer world. Of course, it is impossible to predict the future with absolute certainty. The precise amount of future climate change that will occur over the rest of this century is uncertain for several reasons.

First, projections of future climate changes are usually based on scenarios (or sets of assumptions) regarding how future emissions may change as a result of population, energy, technology, and economics. Society may choose to reduce emissions or to continue to increase them. The differences in projected future climate under different scenarios are generally small for the next few decades. By the second half of the century, however, human choices, as reflected in these scenarios, become the key determinant of future climate change. And human choices are nearly impossible to predict.

A second source of uncertainty is natural variability, which affects climate over timescales from months to decades. These natural variations are largely unpredictable and are superimposed on the warming from increasing heat-trapping gases. Uncertainty in the sun's future output is another source of variability that is independent of human actions. Estimates of past changes in solar variability over the last several millennia suggest that the magnitude of solar effects over this century are likely to be small compared to the magnitude of the climate change effects projected from human activities.

A third source of uncertainty involves limitations to our current scientific knowledge. The Earth's climate system is complex, and continues to challenge scientists' understanding of exactly how it may respond to human influences. Observa-

Emissions Levels Determine Temperature Rises

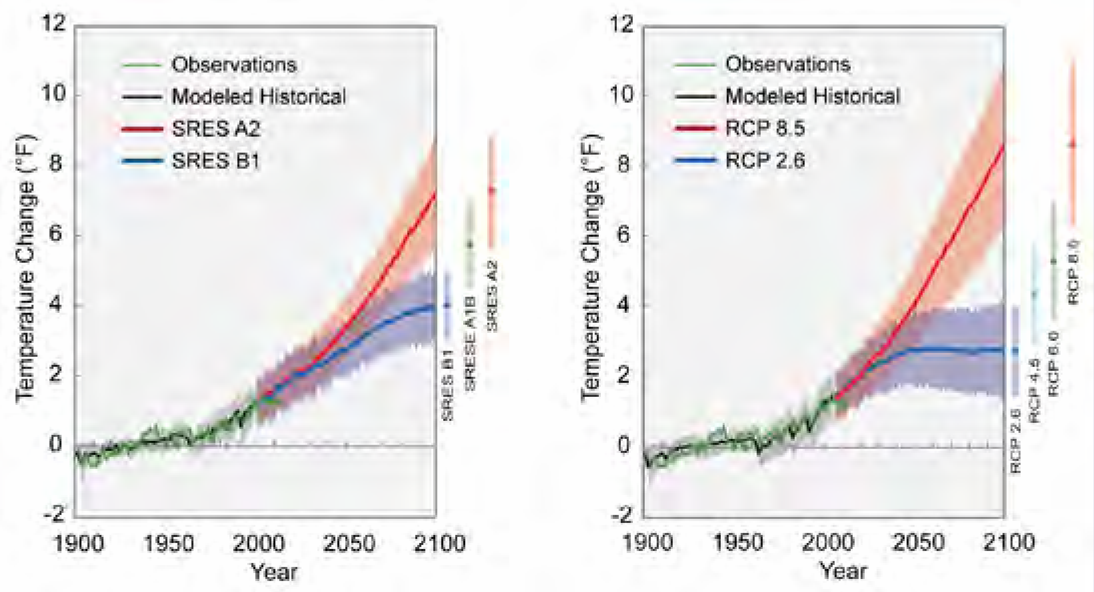


Figure 23. Projected global average annual temperature changes for multiple future scenarios relative to the 1901-1960 average temperature. Each line represents a central estimate of global average temperature rise for a specific emissions pathway. Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. The left panel shows results from the previous generation of climate models (CMIP3), and the right panel shows results from the most recent generation of climate models (CMIP5). Projections in 2099 for additional emissions pathways are indicated by the bars to the right of each panel. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. (Data from CMIP3, CMIP5, and NOAA NCDC).

tions of the climate system have expanded substantially since the beginning of the satellite era, but are still limited. Climate models differ in the way they represent various processes (for example, cloud properties, ocean circulation, and turbulent mixing of air). As a result, different models produce slightly different projections of change, even when the models use the same scenarios. Scientists often use multiple models in order to represent this range of projected outcomes.

Finally, there is always the possibility that there are processes and feedbacks not yet being included in future projections. For example, as the Arctic warms, carbon trapped in permafrost may be released into the atmosphere, increasing the initial warming due to human emissions of heat-trapping gases (see FAQ T).

However, for a given future scenario, the amount of future climate change can be specified within plausible bounds, determined not only from the differences in the "climate sensitivity" among models but also from information about climate changes in the past.

T. Are there tipping points in the climate system?

Most climate studies have considered only relatively gradual, continuous changes in the Earth's climate system. However, there are a number of potential "tipping points" in the climate system – points where a threshold is crossed, resulting in a substantial change in the future state of the climate system, regionally and/or globally.

Scientists have identified several aspects of the climate system that could pass a tipping point and/or change substantially under projected climate change (see Figure 24 for key examples). These tipping points have been identified based on observations of past abrupt climate changes, recent observations showing abrupt changes underway (for example, in the Arctic), process-based understanding of the dynamics of the climate system, and climate simulations showing tipping points in future projections. There is no clear scientific consensus at this time as to whether major tipping points, other than loss of the Arctic sea ice in summer, will be reached during this century.

Some tipping points are more imminent, and some would have larger impacts than others. For example, the rapid decline of Arctic sea ice exposes the darker ocean surface which absorbs increasing amounts of heats and reduces the amount of new seasonal ice formed. This drastic reduction in sea ice can tip the Arctic Ocean into a permanent, nearly ice-free state in summer (Ch.2: Our Changing Climate, Key Message 11). There is some

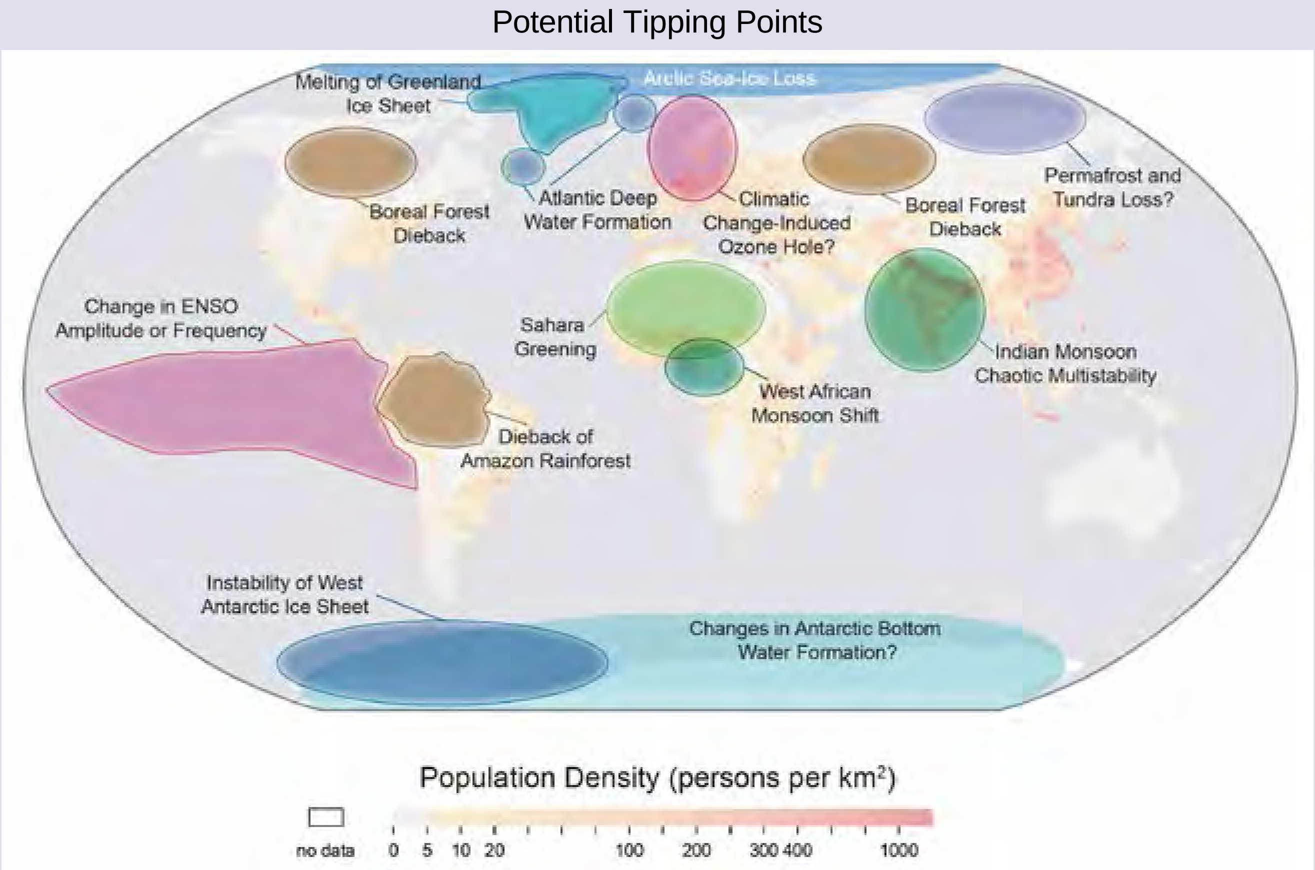


Figure 24. Stylized map of potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain. (Figure source: adapted from Lenton et al. 2008[17])

evidence that reductions in ice cover are already leading to changes in weather patterns affecting the U.S. and Europe.

Currently, the proximity, rate, and reversibility of tipping points are usually assessed through a mixture of climate modeling, literature review, and expert elicitation. However, there is a need for more research in this area. Climate scientists cannot predict when tipping points will be crossed because of uncertainties in the climate system and because we do not know what pathway future emissions will take. But an absence of certainty does not indicate an absence of risk. To use a medical analogy, just because your doctor cannot tell you the precise date and time that you will have a heart attack does not mean you should ignore medical advice to reduce your risk by taking preventative measures like exercising more, losing weight, and changing your diet. Medical science is imperfect, just like climate science, but it can provide very useful advice regarding the risks of our actions and choices – and the benefits of preventative measures.

U. How is climate change affecting society?

Multiple lines of evidence show that climate change is happening as a result of human activities. Climate change is altering the world around us, and these changes will become increasingly evident with each passing decade. Climate change is already leading to more intense rainfall events and other extreme weather patterns. It will lead to more droughts in some areas, more floods in others, and more frequent heat waves in many areas. Changing temperature and precipitation patterns, as well as increasing sea level, are important factors affecting various parts of the United States. For example, the risks associated with wildfires in the western U.S. are increasing, and coastal inundation is becoming a common occurrence in low-lying areas. Water supply availability is changing in many parts of the United States.

Many people are already being affected by the changes that are occurring, and more will be affected as these changes continue to unfold. To limit risks and maximize opportunities associated with the changes, it would be helpful for people to understand how climate change could affect them and what they can do to adapt, as well as what can be done to reduce future climate change by reducing global emissions.

Taking actions to reduce the emissions that cause climate change has costs. Not taking those actions has much greater costs.[18]

Climate change will affect ecosystems and human systems – such as agricultural, transportation, water resources, and health-related infrastructure – in ways we are only beginning to understand. Moreover, climate change interacts with other stressors, such as population increase, land-use change, and economic and political changes, in ways that we may not be able to anticipate, compounding the risks.

In general, the larger and faster the changes in climate, the more difficult it is for human and natural systems to adapt. The climate system has been relatively stable during the time that human civilizations have existed. Essentially, today's built infrastructure has been developed based on the assumption that future climate will be like that of the past. This assumption is no longer valid.

Since climate change is already occurring, adaptation in some form is inevitable. The choice is between proactive adaptation (planning ahead to limit impacts) or reactive adaptation (where responses occur only after damages are already incurred). The *America's Climate Choices* reports from the U.S. National Academy of Sciences discuss these issues in details.

Potential Effects of Climate Change

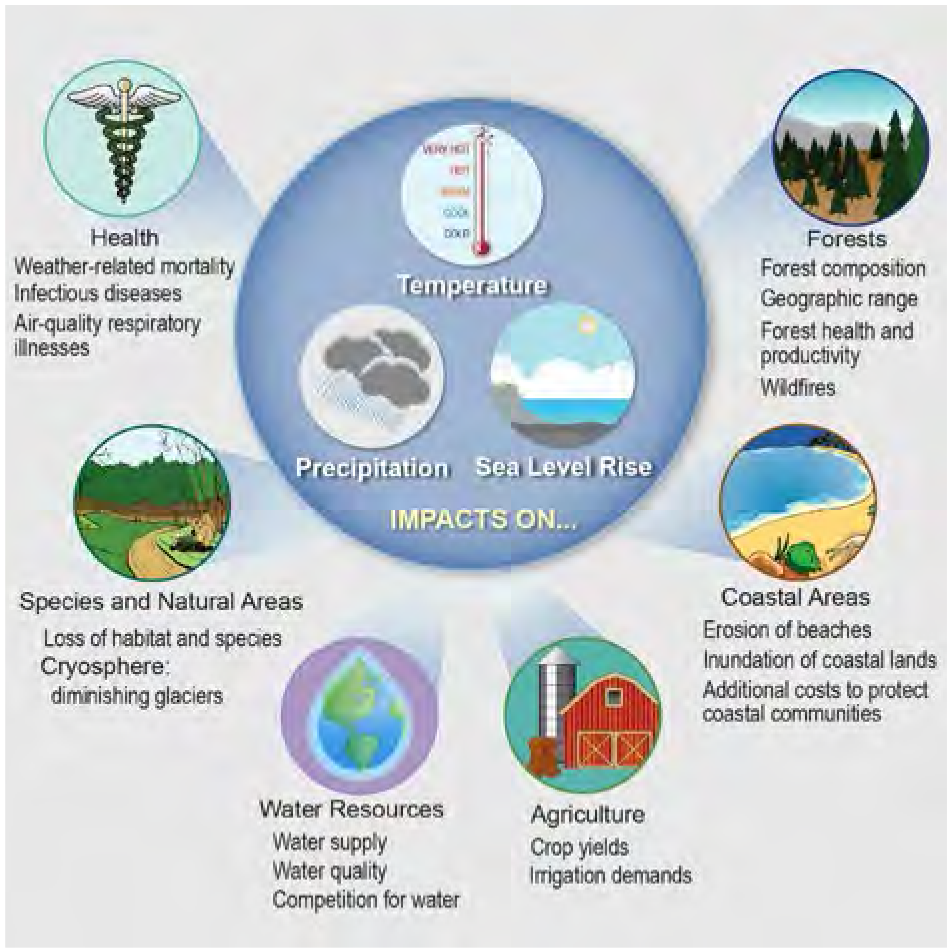


Figure 25. Climate change is likely to affect human society and the natural environment in many ways. The National Climate Assessment's sectoral impacts chapters examine these impacts by category in detail. (Figure source: adapted from Phillipe Rekacewicz UNEP/GRID-Arendal 2012, "Vital Climate Graphics" collection[19]).

V. Are there benefits to warming?

Some climate changes currently have beneficial effects for specific sectors or regions. For example, current benefits of warming include longer growing seasons for agriculture and longer ice-free periods for shipping on the Great Lakes. At the same time, however, longer growing seasons, along with higher temperatures and carbon dioxide, can increase pollen production, intensifying and lengthening the allergy season. Longer ice-free periods on the Great Lakes can result in more lake-effect snowfalls.

Many analyses of this question have concluded that there will be more negative effects than positive ones. This is largely because our society and infrastructure have been built for the climate of the past, and any rapid change from that climate imposes difficulties and costs. For example, many major cities are located on the coasts where they are now vulnerable to sea level rise. And there has been rapid population growth in the U.S. Southwest, where increasing heat and drought threaten water supplies and cause increased wildfires. In addition, ecosystems that we rely on for our food and water are adapted to the cooler climate that our planet has experienced over recent centuries.

W. Are some people more vulnerable than others?

People will be affected by climate change in various ways, but some groups are more vulnerable than others. For example, the poor, the very young, and some older people have less mobility and fewer resources to cope with extremely high temperatures, increased water scarcity, environmental degradation, and other impacts. People living in flood plains, coastal zones, and some urban areas are generally more vulnerable as well.

Children, primarily because of physiological and developmental factors, will disproportionately suffer from the effects of heat waves, air pollution, infectious illness, and trauma resulting from extreme weather events. The country's older population also could be harmed more as the climate changes. Older people are at much higher risk of dying during extreme heat events. Pre-existing health conditions also make older adults susceptible to cardiac and respiratory impacts of air pollution and to more severe consequences from infectious diseases. Limited mobility among older adults can also increase flood-related health risks. Limited resources and an already high burden of chronic health conditions, including heart disease, obesity, and diabetes, will place the poor at higher risk of health impacts from climate change than higher income groups. Potential increases in food cost and limited availability of some foods will exacerbate current dietary inequalities and have significant health ramifications for the poorer segments of our population.

X. Are there ways to reduce climate change?

The most direct way to significantly reduce the magnitude of future climate change is to reduce the emissions of heat-trapping gases. Emissions can be reduced in many ways, and increasing the efficiency of energy use is an important component of many potential strategies. For example, because about 28% of the energy used in the U.S. is used for transportation, developing and driving more efficient vehicles and changing to fuels that do not contribute significantly to heat-trapping gas emissions over their lifetimes would result in fewer emissions per mile driven. A large amount of energy in the U.S. is also used to heat and cool buildings, so changes in building design could dramatically reduce energy use. While there is no single silver bullet that will solve all the challenges posed by climate change, there are many options that can reduce our emissions and help prevent some of the potentially serious impacts of climate change. There will be some costs to these changes, but even very ambitious emissions reductions targets have relatively small costs over the decades it will take to implement them.

Because impacts are already occurring and anticipated to increase, adaptation to the impacts of climate change will be required. Adaptation decisions range from being better prepared for extreme events such as floods and droughts, to identifying economic opportunities that come from investments in adaptation and mitigation strategies and technologies, to integrating considerations of new climate-related risks into city planning, public health and emergency preparedness, and ecosystem management.

Technological fixes such as "geoengineering" may be possible, but at least some such proposals would do nothing to slow ocean acidification, and would need to be done indefinitely. There are a wide variety of potential risks of geoengineering schemes, which are very poorly understood (see FAQ Z).

Multiple Pathways for Reducing U.S. Emissions

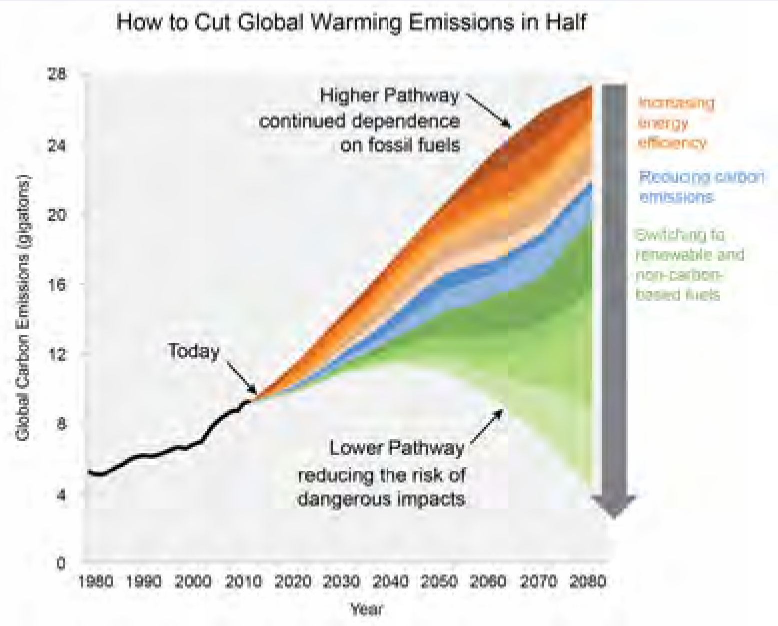


Figure 26. Reducing carbon emissions from a higher pathway (here, RCP 8.5) to a lower pathway (here, RCP 4.5) can be accomplished with a combination of many technologies and policies, illustrated here based on the "wedges" concept pioneered by Pacala and Socolow in 2004.[20] These wedges could include increasing the energy efficiency of appliances, vehicles, buildings, electronics, and electricity generation (orange wedges); reducing carbon emissions from fossil fuels by switching to lower-carbon fuels or capturing and storing carbon (blue wedges); and switching to renewable and non-carbon emitting sources of energy, including solar, wind, wave, biomass, tidal, and geothermal (green wedges). The shapes and sizes of the wedges shown here are illustrative only. (Data from Boden et al. 2012[21]).

Y. Are there advantages to acting sooner rather than later?

The effects of current emissions of carbon dioxide and other heat-trapping gases on climate can take decades to fully manifest themselves. The resulting change in climate and the impacts of those changes can then persist for a long time. The longer these changes in climate continue, the greater the resulting impacts. It will become increasingly costly to adapt, and some systems will not be able to adapt if the change is too much or too fast. Thus it is not surprising that recent reports from the U.S. National Academy of Sciences, including America's Climate Choices[22] and America's Energy Future,[23] have concluded that the environmental, economic, and humanitarian risks posed by climate change indicate a pressing need for substantial action to limit the magnitude of climate change and to prepare to adapt to its impacts. They also concluded that substantial reductions of heat-trapping gas emissions should be among the nation's highest priorities.

The National Academy of Sciences and others have concluded that acting now will reduce the risks posed by climate change and the pressure to make larger, more rapid, and potentially more expensive reductions later. Actions taken to reduce vulnerability to climate change impacts can be considered as investments that can make sense economically, especially if they also offer protection against natural climate variations and extreme events. In addition, investment decisions made now about equipment and infrastructure can "lock in" emissions of heat-trapping gases for decades to come. Finally, while it may be possible to alter our responses to climate change, it is difficult or impossible to "undo" climate change once it has occurred.

Current efforts at local and state levels, and by the private sector, are important, but are insufficient to limit warming to the lower scenarios described throughout this report. Thus, numerous analyses have called for policies that establish coherent national and international goals and incentives, and that promote strong U.S. engagement in international-level response efforts. The National Academy of Sciences found that the inherent complexities and uncertainties of climate change will be best met by applying a risk management approach and by making efforts to significantly reduce heat-trapping gas emissions; prepare for adapting to impacts; invest in scientific research, technology development, and information systems; and facilitate engagement between scientific and technical experts and the many types of people making America's climate choices.

Two U.S. Emissions-Reduction Pathways

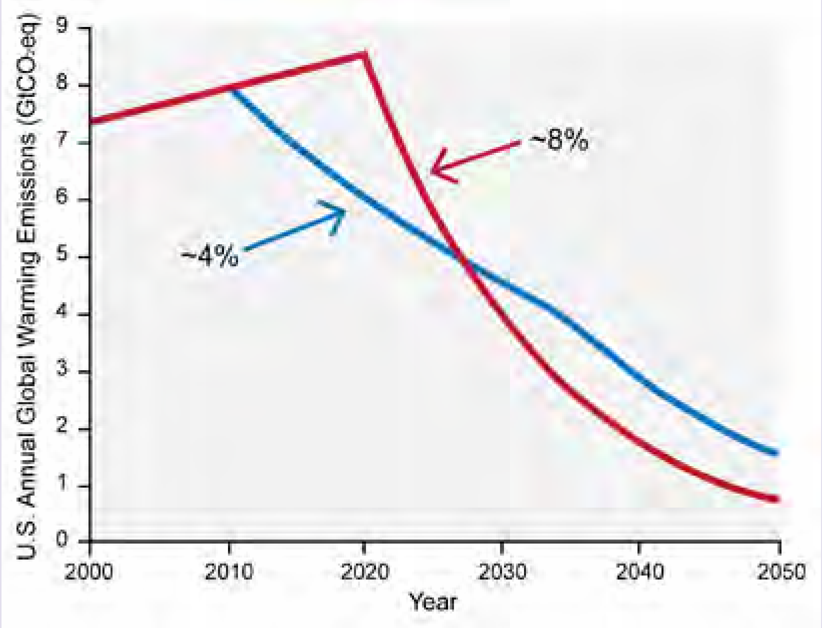


Figure 27. This graph shows how earlier action to reduce U.S. emissions would be less difficult than delayed action. Two pathways show how a cumulative carbon emissions budget of 265 gigatons of CO_2 could be maintained by 2050. By initiating reduced emissions efforts in 2010 (blue line), a 4% per year reduction would have been required; waiting until 2020 to reduce emissions (red line) doubles the rate at which emissions must be reduced. (Figure source: Luers et al. 2007[24])

Z. Can we reverse global warming?

While we can't stop climate change in its tracks, we can limit it to less dangerous levels by reducing our emissions. Even if all human-related emissions of carbon dioxide and the other heat-trapping gases were to stop today, Earth's temperature would continue to rise for a number of decades and then slowly begin to decline. However, focusing on short-lived types of emissions, such as methane and black carbon (soot), can reduce the rate of change in the near term. Because of the complex processes controlling carbon dioxide concentrations in the atmosphere, even after more than a thousand years, the global temperature would still be higher than it was in the pre-industrial period. As a result, without technological intervention, it will not be possible to totally reverse climate change. We do face a choice between a little more warming and lot more warming, however. The amount of future warming will depend on our future emissions.

In theory, it may be possible to reverse global warming through technological interventions called geoengineering. Three types of geoengineering approaches have been proposed to alter the climate system: 1) enhancing the natural processes that remove carbon dioxide from the atmosphere; 2) altering the amount of the sun's energy that reaches the Earth (referred to

Emissions Reductions and Carbon Dioxide Concentrations

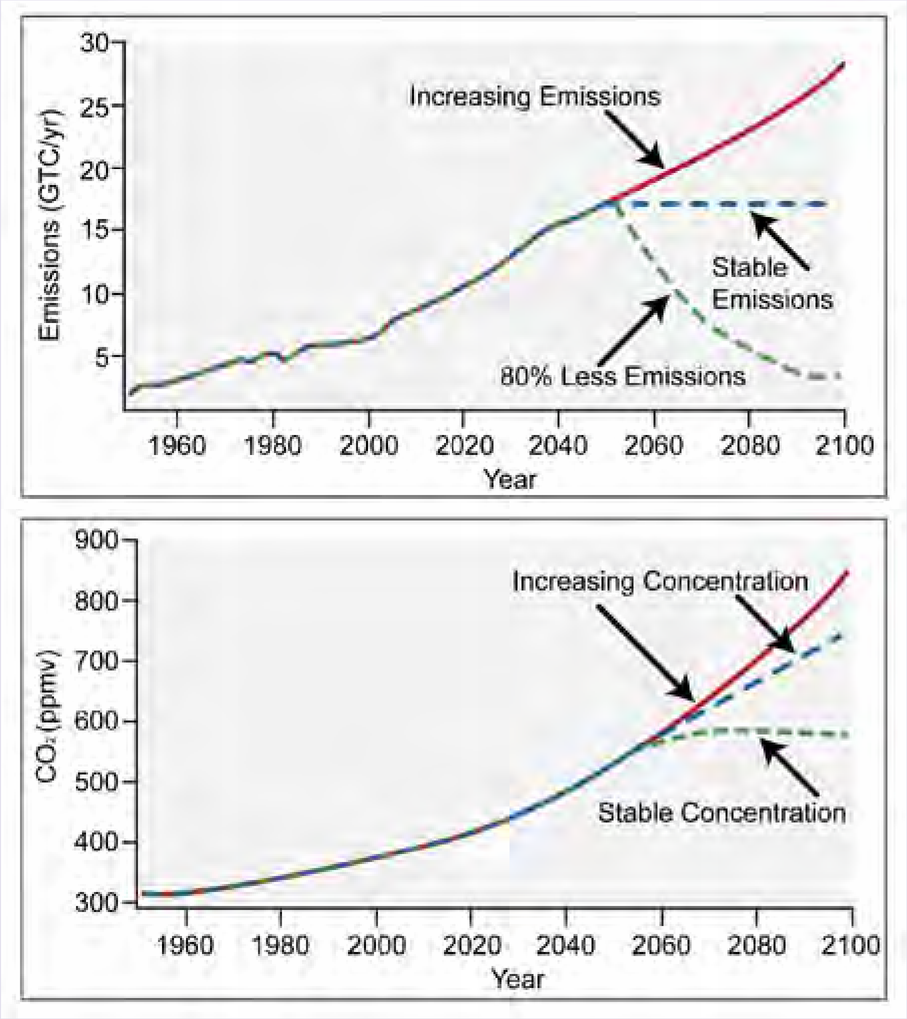


Figure 28. To reduce the changes occurring in climate, we would need to stabilize atmospheric levels of carbon dioxide, not simply stabilize current emission levels of carbon dioxide. Just stabilizing emissions still leads to increasing amounts of carbon dioxide in the atmosphere, because emissions are greater than the sinks that remove it (blue lines). To stabilize levels of atmospheric carbon dioxide, emissions would need to be reduced significantly, on the order of 80% or more compared to the present day (green lines). The lower graph shows how carbon dioxide concentrations would be expected to evolve depending upon emissions for one illustrative case, but this applies for any chosen target. (Figure source: NRC 2011[25]).

as “solar radiation management”); and 3) direct capture and storage of CO_2 from the atmosphere.

Various techniques for removal of carbon dioxide from the atmosphere have been proposed. At this time, however, there is no indication that any of them could be implemented on a large enough scale to have a significant effect. Investments in limiting emissions, combined with capturing and storing carbon, could possibly reverse the warming trend, but it remains to be seen if this is feasible.

Artificial injection of stratospheric particles and cloud brightening are two examples of “solar radiation management” techniques. The cooling effect that some types of particles have on the atmosphere has led to the proposal of an array of possible geoengineering projects, especially with the goal of offsetting the warming until more non-fossil fuel energy is put into place. However, the climate system is complex and experimenting without complete understanding could result in unintended and potentially dangerous side effects on our health, ecosystems, agricultural yields, and even the climate itself. Even if such engineering approaches were economically feasible, the potential impacts on the environment need to be better understood. One important consideration regarding solar radiation management is that ocean acidification would still continue even if warming could otherwise be reduced by reflecting light away from our atmosphere. Much more research is needed to see if such approaches could be environmentally feasible. In the meantime, there are significant concerns about ecological and other side effects of some of these technologies.

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APPENDIX 5 SCENARIOS AND MODELS

Scenarios

Scenarios provide ways to help understand what future conditions might be. Each scenario provides an example of what might happen under particular assumptions, and is neither a prediction nor a forecast. Instead, scenarios provide scientifically rigorous and consistent starting points for examining questions about an uncertain future and help us to visualize alternative futures in human terms. The military and businesses frequently use these powerful tools for future planning in high-stakes situations. Scenarios are used to help identify future vulnerabilities as well as to support decision-makers who are focused on limiting risk and maximizing opportunities. Three types of scenarios are used within this assessment to help frame the impact analyses in a consistent way: emissions scenarios (including population and land-use components); climate scenarios; and sea level rise scenarios. Each is briefly described below.

Emissions Scenarios

Emissions scenarios quantitatively illustrate how the release of different amounts of climate-altering gases and particles into the atmosphere will produce different future climate conditions. Such emissions result from human activities including fossil fuel energy production and use, agriculture, and other activities that change land use. These scenarios are developed using a wide range of assumptions about population growth, economic and technological development, and other factors. A wide range of assumptions is used because future trends depend on unpredictable human choices.

Perspectives on “plausible” emissions scenarios evolve over time. The Intergovernmental Panel on Climate Change (IPCC) has released three different sets of scenarios since 1990. In 2000, the IPCC released a Special Report on Emission Scenarios[1] that provided a set of scenarios, known as the SRES, which described a wide range of socioeconomic futures and resulting emissions. Near the higher end of the range, the SRES A2 scenario represents a world with high population growth, low economic growth, relatively slow technology improvements and diffusion, and other factors that contribute to high emissions and lower adaptive capacity (for example, low per capita wealth). At the lower end of the range, the SRES B1 scenario represents a world with lower population growth, higher economic development, a shift to low-emitting efficient energy technologies that are diffused rapidly around the world through free trade, and other conditions that reduce the rate and magnitude of climate change as well as increase capacity for adaptation. The SRES A2 and B1 scenarios are the foundation scenarios used in this assessment to evaluate future impacts.

Recently, a new set of scenarios (Representative Concentration Pathways – RCPs) has been prepared and released by scientists who study emissions, climate, and potential impacts.[2] This new set incorporates recent observations and research and includes a wider range of future conditions and emissions. Because climate model results are just now being released using the new scenarios, and there are few impact studies that employ them, the RCP climate scenarios are used sparingly in this assessment.

Scientists cannot predict which, if any, of the scenarios in either the SRES set or the RCP set is most likely because the future emissions pathway is a function of human choices. A wide range of societal decisions and policy choices will ultimately influence how the world’s emissions evolve, and ultimately, the composition of the atmosphere and the state of the climate system.

Climate Scenarios and Climate Models

Global models that simulate the Earth’s climate system are used, among other things, to evaluate the effects of human activities on climate. This assessment incorporates a new set of model simulations that have higher resolution and enhanced representation of Earth system physics, chemistry, and biology. These models use the new set of RCP emissions scenarios described above to project expected climate change given various assumptions about how human activities and associated emissions levels might change.

The range of potential increases in global average temperature in the newest climate model simulations is wider than earlier simulations because a broader range of options for human behavior is considered. For example, the lowest of the new RCP scenarios assumes rapid emissions reductions that would limit the global temperature increase to about 3.7°F, a much lower level than in previous scenarios. The emissions trajectory in RCP 8.5 is similar to SRES A2 and RCP 4.5 is roughly comparable to SRES B1 (see Figure 1). These similarities between specific RCP and SRES scenarios make it possible to compare the results from different modeling efforts over time.

Emissions Levels Determine Temperature Rises

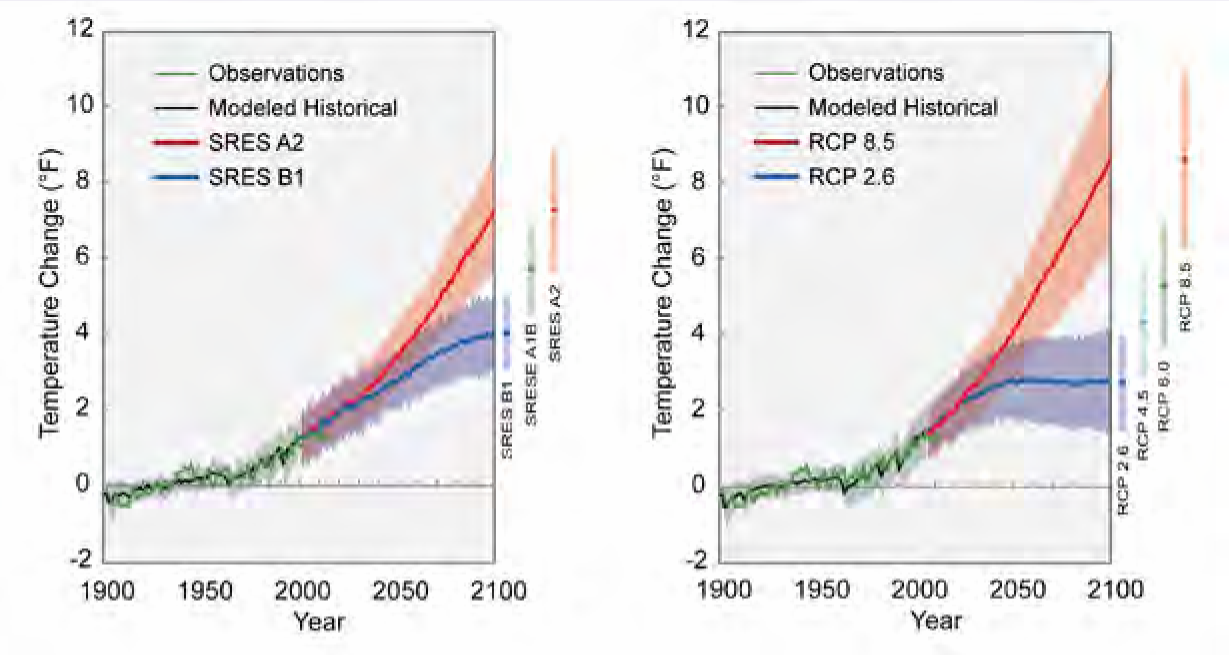

Figure 1. Different amounts of heat-trapping gases released into the atmosphere by human activities produce different projected increases in Earth's temperature. In the figure, each line represents a central estimate of global average temperature rise for a specific emissions pathway (relative to the 1901-1960 average). Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. Projections in 2099 for additional emissions pathways are indicated by the bars to the right of each panel. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. **(Left)** The panel shows the two main scenarios (SRES – Special Report on Emissions Scenarios) used in this report: A2 assumes continued increases in emissions throughout this century, and B1 assumes much slower increases in emissions beginning now and significant emissions reductions beginning around 2050, though not due explicitly to climate change policies. **(Right)** The panel shows newer analyses, which are results from the most recent generation of climate models (CMIP5) using the most recent emissions pathways (RCPs – Representative Concentration Pathways). Some of these new projections explicitly consider climate policies that would result in emissions reductions, which the SRES set did not.[35] The newest set includes both lower and higher pathways than did the previous set. The lowest emissions pathway shown here, RCP 2.6, assumes immediate and rapid reductions in emissions and would result in about 2.5°F of warming in this century. The highest pathway, RCP 8.5, roughly similar to a continuation of the current path of global emissions increases, is projected to lead to more than 8°F warming by 2100, with a high-end possibility of more than 11°F. (Data from CMIP3, CMIP5, and NOAA NCDC).

EMISSIONS SCENARIOS

Two SRES global emissions scenarios were recommended for use by the authors of this report for impact studies. One is a higher emissions scenario (the A2 scenario from SRES) and the other is a lower emissions scenario (the B1 scenario from SRES). These two scenarios do not encompass the full range of possible futures: emissions could change less than those scenarios imply, or they could change even more. Recent carbon dioxide emissions have, in fact, been higher than in the A2 scenario. Whether this trend will continue is not possible to predict because it depends on societal choices.

Sea Level Rise Scenarios

After at least two thousand years of little change, global sea level rose by roughly 8 inches over the last century, and satellite data provide evidence that the rate of rise over the past 20 years has roughly doubled. In the United States, millions of people and many of the nation's assets related to military readiness, energy, transportation, commerce, and ecosystems are located in areas at risk of increased coastal flooding because of sea level rise and associated storm surge.

Global sea level is rising and will continue to do so beyond the year 2100 as a result of increasing global temperatures. This occurs for two main reasons. First, when temperatures rise, ocean water heats up, causing it to expand. Second, when glaciers and ice sheets melt in response to hotter conditions, additional water flows into the oceans. Sea level is projected to rise an additional 1 to 4 feet in this century. Scientists are unable to narrow this range at present because the processes affecting the loss of ice mass from the large ice sheets are dynamic and still the subject of intense study.

Some impact assessments in this report use a set of sea level rise scenarios within this range, while others consider a wider range. Four scenarios (8 inches, 1 foot, 4 feet, and 6.6 feet of rise by 2100), along with explanations regarding how to use this information, are included in a guidance document on sea level rise that was provided to the National Climate Assessment (NCA) authors to use as the basis of impact assessments in coastal areas.[3]

Past and Projected Changes in Global Sea Level

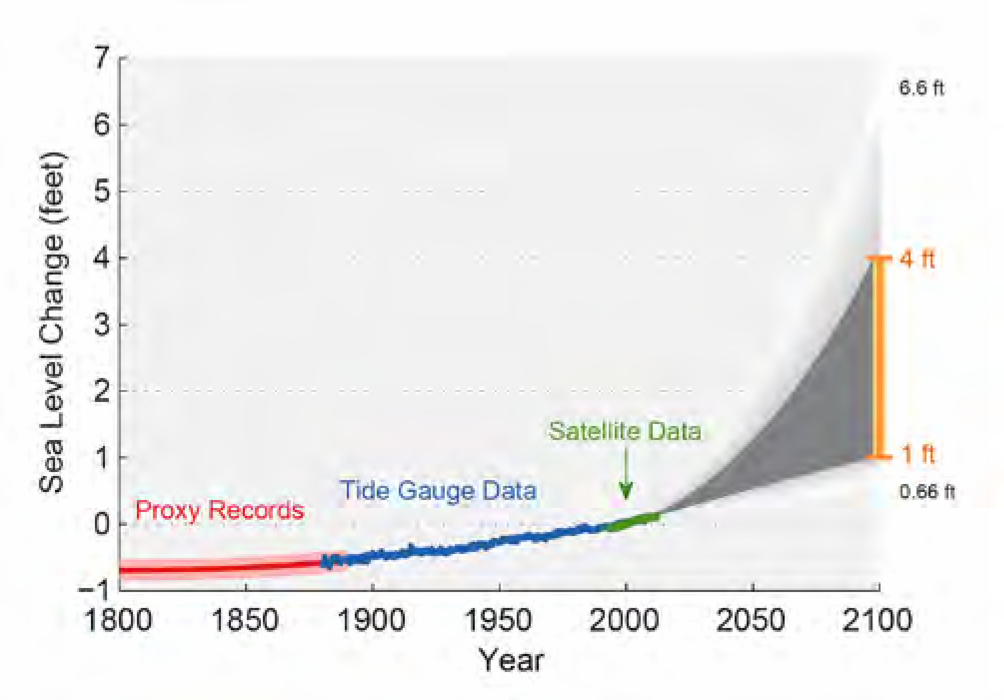

Figure 2. Historical, observed, and possible future amounts of global sea level rise from 1800 to 2100. Historical estimates[4] (based on sediment records and other proxies) are shown in red (pink band shows uncertainty range), tide gauge measurements in blue,[5] and satellite observations in green.[6] The future scenarios displayed here range from 8 inches to 6.6 feet in 2100.3 Sea level rise lower than 8 inches or higher than 6.6 feet is considered implausible by 2100. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100. The large range primarily reflects uncertainty about how ice sheets will respond to the warming ocean and atmosphere, and to changing winds and currents. (Figure source: NASA Jet Propulsion Laboratory).

Models and Sources of Uncertainty

There are multiple well-documented sources of uncertainty in climate model simulations. Some of these uncertainties can be reduced with improved models. Some may never be completely eliminated. The climate system is complex, including natural variability on a range of time scales, and this is one source of uncertainty in projecting future conditions. In addition, there are challenges with building models that accurately represent the physics of multiple interacting processes, with the scale and time frame of the available historical data, and with the ability of computer models to handle very large quantities of data. Thus, climate models are necessarily simplified representations of the real climate system.

One of the largest sources of uncertainty in projecting future conditions involves what decisions society will make about managing the emissions of greenhouse gases. By later this century, very different conditions would result from higher emissions scenarios (such as A2) than from lower ones (like B1).

Over the last decade, concerted efforts in climate modeling have focused on understanding and better quantifying the uncertainties inherent in model simulations of climate change and on improving model resolution and representations of physical and biological processes important to the climate system. It is very clear that progress is being made in the accuracy of models in representing the physics of the climate system at smaller scales. This is demonstrated, for example, by the ability of these models to replicate observed climate.

To understand and better quantify uncertainty, multiple models generated by different modeling groups around the world are being used to identify common features in projections of climate change. The Third Coupled Model Intercomparison Project (CMIP3), and more recently CMIP5, established formalized structures that enable model evaluations against the climate record of the recent past. New elements of the CMIP5 effort include a major focus on near-term, decade-length projections designed for regional climate change and on predictions from the new class of Earth system models that include coupled physical, chemical, and biogeochemical climate processes. CMIP3 findings are the foundation for most of the impact analyses included in this assessment. Newer information from CMIP5 was largely unavailable in time to serve as the foundation for this report and is primarily provided for comparison purposes.

The breadth and depth of these analyses indicate that the modeling results in this report are robust. There is an important distinction to be made, however, between a "prediction" of what "will" happen and a "projection" of what future conditions are likely given a particular set of assumptions. All of the model results presented in this report are the latter: projections based on specified assumptions about emissions. The new regional projections provided in this report represent the state of the science in climate change modeling.[7]

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APPENDIX 6 TOPICS FOR CONSIDERATION IN FUTURE ASSESSMENTS

Although this report covers a broad range of topics related to understanding, assessing, and responding to global change as required by the Global Change Research Act,1 it is not possible to provide a comprehensive analysis of every topic in a single report. The following are important topics that could not be adequately covered in this report. In preparation for future synthesis reports, these are some topics that could be considered.

Economic Analyses

Documenting the costs of climate change impacts is extremely challenging because these impacts occur across multiple regions and sectors and over multiple time frames. The impacts include physical, ecological, and social components, and many are difficult to extract from underlying sources of vulnerability not caused by climate change. Also, while some types of extreme weather events are made more frequent and/or intense by climate change, it is rare that any event has a single cause. Since such events generally result from a combination of natural variability and climate change, it is difficult to assign a precise proportion of the costs associated with a particular event to climate change. Further, many impacts occur in ways that are difficult to translate into precise economic costs; for example, impacts to biodiversity, changes in quality of life, or social stresses are likely to be valued differently by different individuals and communities. Finally, it is challenging to assess the economic implications of rare events, which have low probability but high consequence – especially in cases where there is limited or non-existent data about the costs of such events in the past.

A number of studies have produced estimates of the economic damages expected from future climate change. However, there are currently no total economic damage estimates that are based on valuing and aggregating the various regional and sectoral impacts that are the focus of this assessment. Understanding these impacts in more detail could provide important input for adaptation and mitigation decisions.

National Security

The implications of climate change for U.S. national security are significant, but they have not been analyzed in detail in this report because there are a number of recent unclassified U.S. Department of Defense (DoD) reports and reports of other groups that have rigorously addressed this topic. In 2010, the DoD released the Quadrennial Defense Review (QDR), for the first time acknowledging that climate change will play a "significant role in shaping the future security environment."2 Based on the QDR, the DoD is now incorporating and considering the consequences of climate change in its long-range strategic plans, including potential impacts to its facilities and missions. Other recent reports by the National Intelligence Council and the National Research Council (NRC) analyze the security implications of climate change.3 The NRC found that "It is prudent to expect that over the course of a decade some climate events…will produce consequences that exceed the capacity of the affected societies or global systems to manage and that have global security implications serious enough to compel international response." National security concerns are highly integrated with a variety of other economic, health, policy and resource management issues. The findings of the National Climate Assessment reports, as well as other environmental assessments, are influential in determining threats to national security. It will be useful in future reports to advance the state of knowledge of climate impacts in a manner that would improve the ability of the appropriate government institutions to determine how such impacts are integrated in complex ways with national security concerns and emergency preparedness.

Interactions between Adaptation and Mitigation Activities

An additional topic that requires further investigation is the state of knowledge of the intersections of adaptation and mitigation activities. Although adaptation, preparedness, and resilience are all related concepts, the emissions implications across the life of an adaptation project, including full assessment of the emissions associated with "supply chains" for manufactured goods and services, are difficult to assess for any project, and even more challenging on larger scales. In addition, there are options where mitigation and adaptation strategies have co-benefits and other combinations of strategies that can cause unintended negative consequences. For example, the water resource implications of increased production of biofuels are substantial in some regions of the United States, and may result in negative impacts on ecosystems, power production, or residential water supply (see Ch. 6: Agriculture; Ch. 10: Energy, Water, and Land; Ch. 27: Mitigation; and Ch. 28: Adaptation). It would be useful to explore these and related topics in more detail in future assessments.

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ABBREVIATIONS AND ACRONYMS

AMAP – Arctic Monitoring and Assessment Programme

AR4 – IPCC Fourth Assessment Report

C2ES - Center for Climate and Energy Solutions

CDC – Centers for Disease Control and Prevention

CDP – Carbon Disclosure Project

CDR – Carbon Dioxide Removal

CEQ – White House Council on Environmental Quality

CCSP – Climate Change Science Program

CICS-NC – Cooperative Institute for Climate and Satellites, North Carolina

CMIP3 – Coupled Model Intercomparison Project, 3rd phase

CMIP5 – Coupled Model Intercomparison Project, 5th phase

CO_2 – Carbon Dioxide

DOC – U.S. Department of Commerce

DoD – U.S. Department of Defense

DOE – U.S. Department of Energy

DOI – U.S. Department of the Interior

DOT – U.S. Department of Transportation

EIA – Energy Information Administration

ENSO – El Niño-Southern Oscillation

EPA – U.S. Environmental Protection Agency

ERS – Economic Research Service

FAO – Food and Agriculture Organization

FEMA – Federal Emergency Management Agency

FIA – Forest Inventory Analysis

FWS – U.S. Fish and Wildlife Service

GAO – Government Accountability Office

GCIS – Global Change Information System

GCRA – Global Change Research Act

GHG – Greenhouse Gas

GPS – Global Positioning System

GRACE – Gravity Recovery and Climate Experiment

GWP – Global Warming Potential

ICCATF – Interagency Climate Change Adaptation Task Force

INCA – Interagency National Climate Assessment Working Group

IPCC – Intergovernmental Panel on Climate Change

NASA – National Aeronautics and Space Administration

NCA – National Climate Assessment

NCADAC – National Climate Assessment and Development Advisory Committee

NCDC – National Climatic Data Center

NCEP – National Center for Environmental Prediction

NCO – National Coordination Office

NDMC – National Drought Mitigation Center

NESDIS – National Environmental Satellite, Data, and Information Service

NGO – Non-governmental Organizations

NIDIS – National Integrated Drought Information System

NOAA – National Oceanic and Atmospheric Administration

NPS – National Park Service

NRC – National Research Council

NRCS – Natural Resources Conservation Service

NSF – National Science Foundation

NSTC – National Science and Technology Council

NWS – National Weather Service

OMB – White House Office of Management and Budget

OSTP – White House Office of Science and Technology Policy

RCP – Representative Concentration Pathways

RGGI – Regional Greenhouse Gas Initiative

RISA – Regional Integrated Sciences and Assessments

SGCR – Subcommittee for Global Change Research

SOCCR – State of the Carbon Cycle Report

SRES – Special Report on Emissions Scenarios

SST – Sea Surface Temperature

TIR – Technical Input Report

TSU – Technical Support Unit

UCAR – University Corporation for Atmospheric Research

UNEP – United Nations Environment Programme

USACE – U.S. Army Corps of Engineers

USDA – U.S. Department of Agriculture

USFS – U.S. Forest Service

USGCRP – U.S. Global Change Research Program

USGS – U.S. Geological Survey

WGA – Western Governor’s Association

WSWC – Western States Water Council

U.S. National Climate Assessment

This report summarizes the science of climate change and the impacts of climate change on the United States, now and in the future.

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