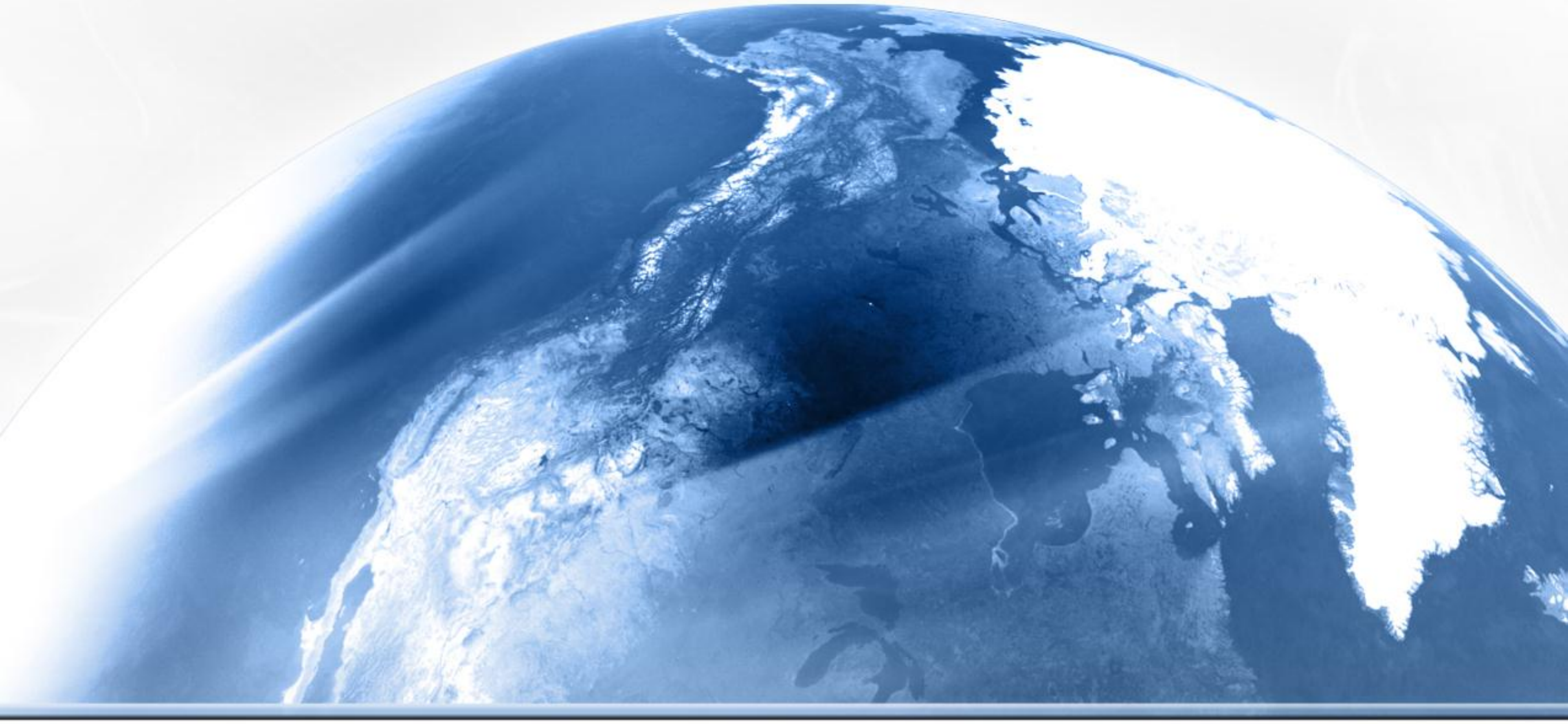
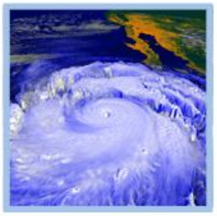


Climate Extremes:
Recent Trends with Implications for National Security

October 2012

Preface

The extent and pace of climate changes will lead to potential impacts on food, water, energy and economic security. Observed change in the climate system is an issue of ongoing concern for the US. Recent unusual extreme weather phenomena worldwide, such as droughts, floods, severe storms, and heat waves raise the specter of significant impacts of changing climate in the near term. The authors sought to consider what one could expect in the period of the next decade – would these anomalous climate extremes persist? To what extent are the extreme conditions a result of natural variability or greenhouse warming, and what are plausible impacts on U.S. national security interests? The authors conclude that the early ramifications of climate extremes resulting from climate change are already upon us and will likely continue to be felt over the next decade – affecting human security and impacting U.S. national security interests.

Acknowledgements

The judgments provided in this report are solely those of the principal authors listed here and not judgments of other scientists who contributed to the study.

Dr. Michael McElroy	Harvard University
Dr. D. James Baker	Former Administrator, National Oceanic and Atmospheric Administration

The authors acknowledge the following individuals for their reviews of the report.

Dr. James G. Anderson	Harvard University
Dr. Mark Cane	Lamont-Doherty Earth Observatory
Dr. David R. Easterling	National Oceanic and Atmospheric Administration
Dr. Peter Huybers	Harvard University
Dr. Gerald A. Meehl	National Center for Atmospheric Research
Dr. Edward S. Sarachik	University of Washington
Dr. Daniel P. Schrag	Harvard University
Dr. Leonard Smith	London School of Economics and Political Science
Dr. Kevin Trenberth	National Center for Atmospheric Research
Dr. John Michael Wallace	University of Washington

Although the reviewers listed above provided many helpful suggestions, they were not asked to endorse the conclusions or recommendations.

The authors also acknowledge the key contribution regarding climate extremes and human security of Mr. Marc Levy, Columbia University.

This study was conducted with funds provided by the Central Intelligence Agency. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the CIA or the US Government.

Table of Contents

List of Figures

List of Tables

1 Introduction

CLIMATE EXTREMES AND NATIONAL SECURITY – THE BOTTOM LINE

Climate change has entered the mainstream as a potential threat to U.S. national security. The 2010 Quadrennial Defense Review, and the 2010 National Security Strategy all identify climate change as likely to trigger outcomes that will threaten U.S. security. These assessments have had to rely on projections of climate change tuned to identify impacts over roughly a one-century time frame. This time frame is driven by the nature of the questions that dominated the initial literature (e.g., what impacts can be expected from a doubling of pre-industrial carbon dioxide) and the fact that global climate models are generally able to resolve expected impacts only over large scales and the long term.

Having arrived at a condition where climate change has been identified as a likely threat to U.S. national security interests, but with little ability to clarify the nature of expected climate impacts over a timeframe that is relevant to security decision-makers, the authors decided to focus on the near-term impacts from climate change (over the next decade). In short, the analysis finds that, absent unknown or unpredictable forces, the increase in extreme events observed in the past decade is likely to continue in the near term as accelerated warming and natural variability combine to produce changing weather conditions around the world. This will impact Water Security, Energy Security, Food Security, and Critical Infrastructure, and brings into focus the need to consider the accelerating nature of climate stress, in concert with the more traditional political, economic, and social indicators.

The observational record shows that the world has been beset with a decade of unusual weather conditions. Droughts, stronger storms, heat waves, floods, wildfires, and anomalous seasonal weather have been outside historical expectations. We find all of this is consistent with a warmer climate, wetter in some areas, drier in others. This warming is driven by radiative energy imbalance resulting from increasing atmospheric concentrations of greenhouse gases. Greenhouse warming is expected to continue in the coming decades and may in fact accelerate, through the removal of cooling aerosols. Attendant oceanic and atmospheric conditions will likely lead to persistent and amplified extreme weather events and climatic conditions in the coming decade, though natural variability will modulate (both worsening and ameliorating) these conditions.

In light of the potential national security ramifications of observed climate and environmental changes, the authors sought to examine whether the increasing numbers of extreme events and manifestations of change are rooted in human-induced climate change, they can be explained as a consequence of decadal manifestations of natural weather variability, or both. Much of the current literature discussing climate change looks to the distant future, 2030 and beyond. The focus in this report is to examine expectations regarding extreme events in the next decade that can provide useful guidance to national security planning. Will extreme weather patterns worsen or continue to persist? Will we witness new manifestations of extreme weather? Would this affect U.S. national security interests? To accomplish this, the authors called on experts in the field and to conduct necessary analyses to shed light on these questions. The authors identify critical information gaps in our understanding of climate change and recommend appropriate measures to address these gaps, so we may better understand in the near term as a result of the apparent transformations at play in Earth's climate.

Examination of the impacts of near-term (less than a decade) climate change poses challenges. To date, most analyses have relied on projections of climate change constructed to identify impacts over roughly a one-century time frame. This time frame is driven by the nature of the questions that dominated the initial literature (e.g., what impacts can be expected from a doubling of pre-industrial carbon dioxide) and the fact that climate models are able to resolve expected impacts only over the long-term. Focusing on climate stress over the next decade requires a different assessment of climate science. Although global models can be used for general guidance, starting with century-scale impacts and interpolating to the near term does not suffice. The global models often fail to capture the dynamics important over the near term, and the models as yet do not provide robust regional forecasts. Instead, one must piece together from first principles the physical dynamics that are likely to generate significant impacts, evaluate the signals available in the observational record, and assess plausible societal responses to such changes.

To this end, the authors undertook a careful examination of the physical drivers that influence weather and that underlie changes in the climate system. They reviewed current literature, examined the record of recent observations and model results, and consulted with scientists familiar with the dynamics of weather, climate, and society. The authors thus combined the best insights of natural and social scientists to examine the extent and pace of near-term climate changes and consequences of the resulting stresses placed on people and nature. In this way, the authors formulated the elements of the scientific framework – theory and observation – required to examine the mechanisms at play for recently witnessed climate changes and extreme weather conditions, in order to assess what can be expected in the next decade.

Dr. Michael McElroy of Harvard University and Dr. D. James Baker, former NOAA Administrator, are the principal authors of this report. Mr. Marc Levy, Columbia University, led the effort to evaluate societal consequences. The judgments provided in this report are solely those of the principal authors and do not necessarily reflect the views of other scientists who participated in workshops or provided critical review.

The principal interaction with the science community took place during three formal workshops:

1. The Social Science Workshop on Societal Impacts of Near-Term Climate Stress, held on 16-17 November 2011 at Columbia University
2. The Physical Science Workshop on Extreme Weather and National Security, held on 29 November 2011 at Harvard University
3. The Joint Workshop on Changing Weather: Implications for Global Stability and National Security, held on 16-17 February 2012 at the National Academy of Sciences in Washington, DC.

The Appendix to this report lists the participants of all three workshops.

Subsequent informal discussions with scientists were undertaken to clarify various points of view. The authors particularly acknowledge those scientists who provided in-depth review and critique of drafts of this report (see Acknowledgements). The authors also acknowledge researchers that provided approval for use of their materials in this report. The authors also commissioned an empirical analysis, leveraging open-source temperature and precipitation data. By examining a one-hundred-year terrestrial record of temperature and a sixty-year record of precipitation, coupled with a global hydrological model, the analysis provided insights with respect to recent decadal trends in extreme temperature and precipitation events, and their impact on fresh water resources.

CLIMATE AND WEATHER EXTREMES

"Climate is what you expect, weather is what you get!"

— Attributed to Robert Heinlein, Mark Twain, and many others —

Climate is essentially the statistical distribution of weather variables (temperature, precipitation, humidity) or general conditions (hot, cold, dry, wet) that are experienced in a region over a period of time, often estimated using thirty years of observational experience. A climate extreme is a value that crosses a prescribed statistical threshold. Climate statistics can be used to quantify the rarity of an extreme weather event (for example, a one in fifty year torrential rain) or extreme weather condition (a severe drought). "Climate extreme" is not to be confused with an "extreme climate" - that of Antarctica, the Sahara desert, or the planet Venus. An extreme weather event is generally said to be so due to its severe impact on people or nature, and is thus of national security interest. This report will use the appropriate term "climate extreme" or "weather extreme" depending on its context. We note that there is also "high impact" weather, not necessarily extreme, but having disproportionate societal impact. This will also be of national security interest.

Chapter 2, The National Security Implications of Climate Extremes, provides an assessment of plausible U.S. national security implications resulting from persistent or worsening climate extremes. Chapter 3, Current Understanding of the Climate System, explores the physical basis that connects Earth's radiation imbalance, climate changes, natural variability and extreme weather, concluding that worldwide anomalous patterns are consistent with the physical changes expected as a result of the interplay of human-induced climate change and the natural mechanisms that induce variability. Chapter 4, The Observational Record, examines the empirical record that leads to the central finding that changing extreme weather conditions, that is, conditions outside expectations, are occurring worldwide, affecting people, societal infrastructure, and the ecosystem services on which societies depend. Chapter 5, Expectations for the Near-Term Future, proposes that accelerated greenhouse gas warming points to continuing, and potentially worsening, extreme weather conditions absent unpredictable or unknown forces that would reverse the increasing radiative imbalance between the Earth and its solar environment. Chapter 6, Recommendations, provides a summary of data needed to maintain and constructively enhance the observational record necessary to monitor, model and better understand the situation as it unfolds in coming years. Chapter 7, Climate Extremes: Principal Findings and Conclusions, provides a synopsis of key results.

2 National Security Implications of Climate Extremes

IMPACTS ON WATER, FOOD, ENERGY SECURITY, AND CRITICAL INFRASTRUCTURE

The conventional approach to assessing the impacts of climate change – that they will unfold only slowly and in the distant future following pathways to which society can easily adapt – is inadequate. Impacts that were once thought of as threatening future societies have been telescoped suddenly into the present, and some consequences are stark. The risk of major societal disruption from weather and climate extremes such as droughts, floods, heat waves, wildfires, and destructive storms is already with us, and expected to increase. Changes of the magnitude we are witnessing already threaten water availability, food security, energy decisions, and critical civil and defense infrastructure. The rapid loss of permanent Arctic ice could result in a cascade of climate feedbacks that lead to irreversible change. We can no longer assume that the extremes of tomorrow will resemble the extremes of yesterday. This creates an imperative to monitor and evaluate impacts upon U.S. national security interests as nations adapt to environmental changes and respond to unfolding events. To do so effectively will require that we sustain and augment our scientific and technical capacity to observe key indicators, monitor unfolding events, and forewarn of important changes.

2.1 Summary

Increasingly prevalent extreme weather phenomena such as droughts, floods, severe storms, and heat waves raise the specter of significant impacts due to changing climate in the near term. Because of the potential proximate threat to U.S. national security interests, the authors undertook a study to consider what one could expect in the next decade: Will these patterns of weather and climate extremes persist? To what extent are the extreme conditions a result of natural variability or greenhouse warming? What are plausible impacts on U.S. national security interests?

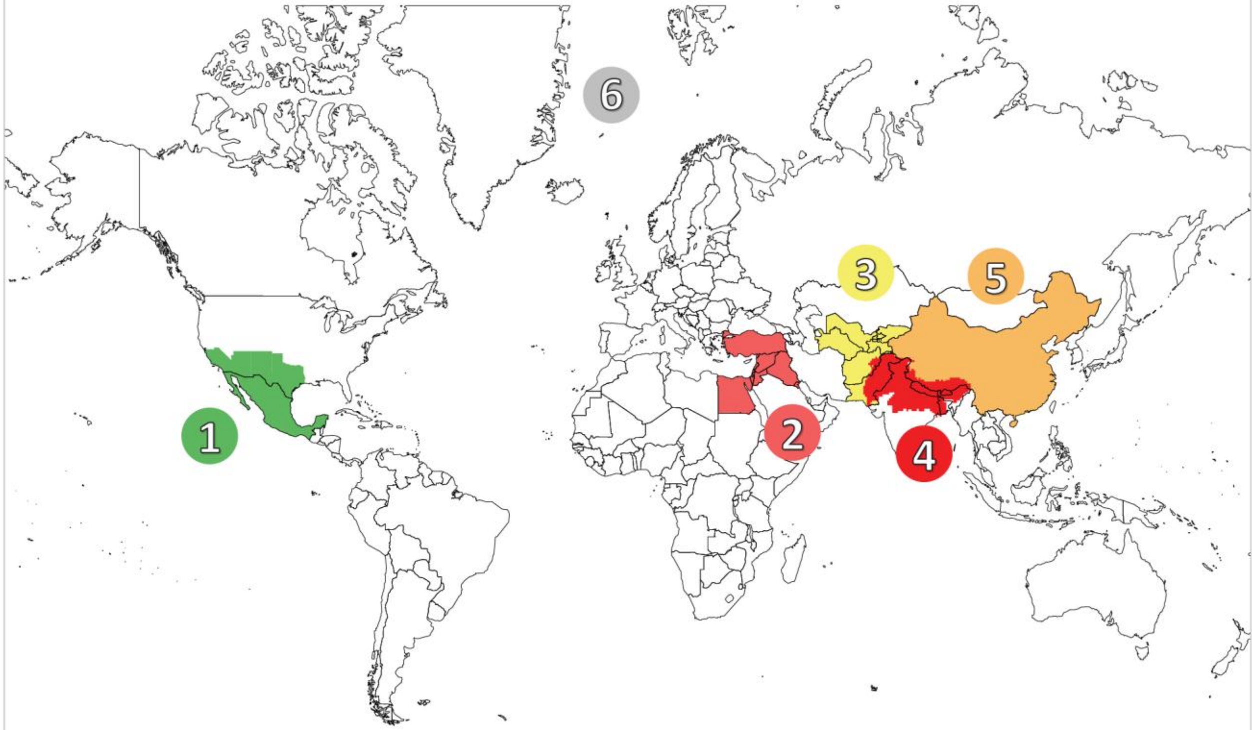
While climate extremes are a fact of nature, the study finds clear evidence that recent prevalence of events and conditions have exceeded expectations based on the past century of weather and concludes, *"The conventional approach to looking at the impacts of climate change – that they will unfold only slowly and in the distant future following pathways to which society can easily adapt – is inadequate."* The study further finds:

1. **Impact of extreme weather:** Evidence is pointing to the fact that human-driven changes in Earth's energy balance are driving a warmer and wetter atmosphere, with this trend superimposed on and magnifying natural variability. Small positive changes in the global mean annual temperature are causing an increased prevalence of local extreme weather conditions. Over the next few years – driven by a combination of natural variability, a warmer climate from the effects of greenhouse gases, and a more vulnerable world in general – the risk of major societal disruption from weather and climate-related extreme events can be expected to increase. *These stresses will affect water and food availability, energy decisions, the design of critical infrastructure, use of the global commons such as the oceans and the Arctic region, and critical ecosystem resources. They will affect both poor and developed nations with large costs in terms of economic and human security.*

2. **The national security context:** It appears that the impacts of climate changes are more imminent than previously thought – a cause for significant concern in the latter part of this century, but affecting society in significant ways today and in the coming decade. The important societal implication of global warming in the near term is not that portions of the earth are going to experience higher temperatures, increased precipitation and increased droughts; it is that the extremes are likely to become more prevalent and more frequent. What was once a 1 in 100 year anomaly is likely to become a 1 in 10 or 1 in 30 year anomaly or even more frequent in the near future. Our infrastructure and agriculture is not designed to accommodate the increasing frequency and prevalence of such extremes. Human security and the interests of most nations are at stake as a result of such increasing climate stress. The national security context will change. The potential for profound impacts upon water, food and energy security, critical infrastructure, and ecosystem resources will influence the individual and collective responses of nations coping with climate changes. U.S. national security interests have always been influenced by extreme weather patterns. Now the risks will become larger and more apparent. *The study renders the judgment that the increasingly disruptive influences of climate extremes necessitate their careful consideration in threat analysis, mitigation, and response.* It is in the best interest of the U.S. to be vigilant about extreme weather patterns, the behavior of nations in their attempts to mitigate or adapt to the effects of changing extremes, and impacts on social, economic, and political well-being.

3. **Regional effects of near-term climate stress:** Regional trends are driven by large-scale features of the climate system such as the ocean sea surface temperatures, the atmosphere's water vapor holding capacity, and atmospheric circulation patterns. One can expect increased warming worldwide with amplification in the Arctic, a warmer ocean, increasing storm intensity in the tropical regions, generally drier subtropical regions, likely wetter conditions in temperate and boreal regions with more intense and less frequent precipitation events, and the increased likelihood of wildfires. Regional prediction remains challenging and will require focused efforts to maintain and enhance Earth observations, especially of the oceans. However, as exemplified by warming, climate extremes will intensify. The effects will be worldwide and will impact all nations. The box below highlights some of the changes we expect to see in selected regions that are highly relevant to US national security interests.

IMPACT OF EXTREME WEATHER TRENDS ON SELECTED REGIONS



1 **Mexico and Southwest United States**
Changes in the Hadley Cell circulation patterns are expected to drive a hotter, drier climate with attendant expansion of desert and arid zones, though patterns will be dominated by natural variability. This region is also vulnerable to both Pacific and Atlantic hurricanes, which are expected to become less frequent but more intense and, therefore, more destructive.

2 **Eastern Mediterranean Region**
The recent amplification of freshwater deficits since the early 1980s is consistent with an expanding Hadley Cell. This suggests that more extensive droughts are likely in a region with chronic water stress and long-standing security issues.

3 **Southwest Asia**
Already a water scarce region, continued expansion of the Hadley Cell would imply a hotter, drier regional climate with attendant expansion of desert and arid zones. This could amplify recent tensions over the management of transnational waterways in the region.

4 **Indus, Ganges, and Brahmaputra Region**
Annual precipitation in the Indus, Ganges, and Brahmaputra river basins is dominated by the South Asian monsoon and dependent upon melt water from the Himalayan region. In the short term, warming influences on the South Asian monsoon point to amplified natural variability leading to a less reliable monsoon, and a likely increase in extreme precipitation. Hence, one can expect to see increased flooding throughout the region.

5 **China**
Large portions of China lie in the subtropical regions likely to be affected by an expanding Hadley Cell. Weather and climate conditions in this region are dominated by a combination of natural variability, a warming trend, and recent regional industrialization causing large emissions of aerosols from coal-fired power plants. As new policies reduce aerosols and warming continues, enhanced extremes are now evident and likely in the near future.

6 **Arctic Region**
The total volume of Arctic sea ice shrank in the summer of 2012 to the smallest amount ever observed during the age of satellites. The transition to summer season ice-free status is now well underway and could happen within a few decades. This shift has already injected sovereignty disputes, jurisdictional claims, resource competition, and military capacity expansion into the national security considerations for the region.

2.2 Discussion

The publication of this report comes at a time when the U.S. has just seen the grip of widespread and severe drought. The drought has affected agricultural productivity and more. For example, nuclear power production in the U.S. was measured at the lowest seasonal levels in nine years as drought and heat forced reactors to slow output. The United States has faced severe climate stress before. The impact of the dust bowl in the early 1930s is imprinted in the memory of our nation’s history. That event was made worse by poor land-use management. The intensity and scope of the current drought combined with record high temperatures reawakens images of the dust bowl era. The affected areas of the dust bowl period were widespread in the United States and Northern Europe. Today we again find widespread drought in many important parts of the world at the same time. Water resources, while already much in demand and inefficiently used in certain critical regions, are thus further stressed due to this extreme weather. The impact of this unfolding event on people and how it may echo through the world markets has yet to play itself out. However, it certainly bears watching, as the world is more vulnerable today than it was in the 1930s.

The worldwide droughts of 2012 are not a singular event of late. As this report shows, it appears that we have experienced an unusual number of weather events throughout the past decade, and some have affected U.S. interests as is illustrated in the foldout panels below. For example, the major drought and heat waves in Russia in 2010 led to major wheat crop failures that influenced the international market place. Are these events harbingers of a changing climate, or part of natural variability? Or, do we see a proximate threat? In either case, as society rapidly becomes more vulnerable, scientists have warned of the impacts of forthcoming climate stress – a new threat to human security in future decades. Whatever the underlying cause, what will unfold in the coming decade is of concern. Will the current pattern of extremes persist, worsen, or ameliorate in the coming decade? The mounting evidence indicates a growing threat that the consequences of natural variability will be much greater as the extremes are magnified by the influences of climate change.

With weather and climate extremes, as with any threat our nation faces, there is a fundamental imperative to observe, monitor, and study related factors to provide insight and objective analysis to our nation’s policy makers about the implications to U.S. national security interests. *Changes of the magnitude we are witnessing have implications for food, water, and energy security*. We design our society, including its infrastructure and its defense apparatus, around expectations, including climate, the expectations of weather patterns and events. Climate is and has always been a natural constraint on national power and prosperity. It has not been perceived as a threat, only a surrounding condition that must be accommodated in both tactical and strategic planning. However, we can no longer assume that climate is fixed and unchanging. The scope of recently observed extreme events and the prospect of future changes that could drive more extreme weather warrant close attention. We can no longer assume that the extremes of tomorrow will resemble the extremes of yesterday.

This study reveals:

1. Impact of Extreme Weather

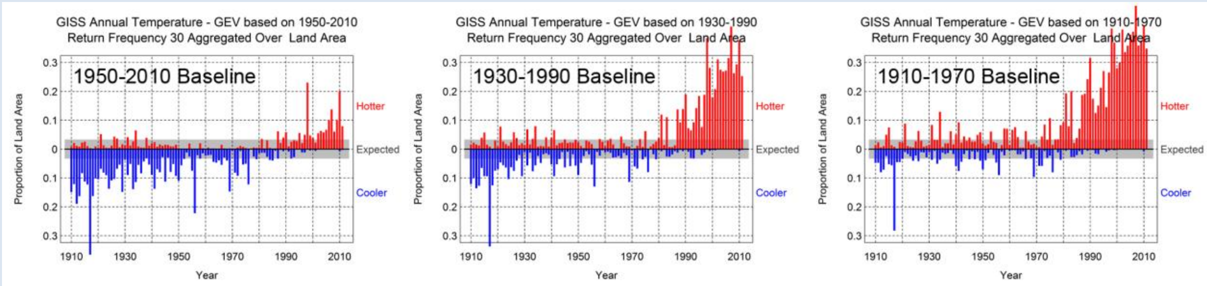
Over the next few years, driven by a combination of natural variability, a warmer climate from the effects of greenhouse gases, and a more vulnerable world in general, the risk of major societal disruption from weather and climate extremes such as droughts, floods, heat waves, wildfires, and destructive storms is expected to increase. These stresses will affect water and food availability, energy decisions, the design of critical infrastructure, and the use of the commons. They will have large costs in terms of both economic and human security. (See box below: Trends in the Prevalence of Extreme Temperatures.)

A more vulnerable world: More prevalent extreme weather can be expected to have a comparatively disproportionate social and economic impact on human societies today, with or without its recent amplification and whatever the cause. That is because society has changed. Increased population; growing industrial infrastructure; urban growth and burgeoning mega cities; increased habitation of coastal regions; growing dependency on water resources to satisfy agricultural, industrial, energy, and domestic needs are all characteristics of a human society with increasing reliance on nature's services. Without deliberate adaptation, the human toll of extreme events will continue to mount and the escalation of extreme events as the climate warms will only make matters worse. Social and climate changes interact to increase insecurity as society struggles to meet greater demand with an increasingly degraded environment.

Impacts on water security: Severe weather conditions directly impact the hydrological cycle and the availability of fresh water resources. Global freshwater withdrawals have increased approximately eight-fold in the last century. Exploitation of water that makes it unavailable for subsequent use by downstream users has increased about five-fold in the last century. These trends are projected to continue well into the 21st century. With an expected increase in the numbers of floods and droughts, many countries important to the U.S. could face environmental stress that may lead to responses and adaptations that, in turn, may present opportunities or challenges to U.S national security interests. Large scale migrations, political realignments, increased competition over resources, changes in economic policy, price shocks, and possible conflict over increasingly scarce water resources and transboundary waters, even failure of marginal states, are all plausible.

Challenges to food security: Food production, already in increased demand, will suffer with more heat extremes and increased variability of rainfall, leading to instability in the food markets. Over the past four years, major spikes in global food prices have arisen from a perfect storm consisting of widespread drought in multiple major agricultural regions, diversions of commodity grain for biofuel production, and increasing demand from rapidly growing economies such as India and China.

TRENDS IN THE PREVALENCE OF EXTREME TEMPERATURES



The prevalence of annual average temperature extremes of the past decade is greater than for any other period in the past one hundred years. In the graphs above, red bars indicate the proportion of the measured land area of the Earth that experienced an annual average temperature hotter than would be expected to occur once in thirty years and blue bars indicate the proportion of the measured land area of Earth where the annual average temperature was cooler than what would be expected to occur once every 30 years. Climate norms were estimated using three baseline periods: the 61-year period from 1950 through 2010 on the left, the 61 years beginning in 1930 in the middle, and the 61 years beginning in 1910 on the right – effectively a climate for each of three generations. Relative to the early 20th century climate norms, our grandparents' generation, over 30% of the land surface has recently experienced abnormally warm weather as compared to the expected long-term average value of about 3% that experienced such conditions during the period 1910 through 1970. Over the past 15 years, cold extremes have become far less frequent. Today's climate is not our grandparents' climate.

Implications to energy security: Emissions from energy-based fossil fuel combustion are the largest human contribution to greenhouse gas concentrations. The energy production infrastructure, requiring copious amounts of water, is often located in regions susceptible to drought, flood, and damaging storms that are expected to become more prevalent in the coming decade. It is, therefore, vulnerable to disruption due to extreme weather. Nuclear power generation is also sensitive to heat waves. During the 2012 heat wave, reactors have been shut down because incoming cooling water was too warm. Large-scale geoengineering efforts to counter the impact of fossil fuel emissions are being developed, but little is known about the impacts of these efforts. There is also a notable absence of workable mechanisms for diplomatic coordination for geoengineering projects.

Threat to critical societal infrastructure: The probability of a major storm crippling a megacity will increase because storms will become more destructive, there will be more flooding from the surge from higher sea-levels, and there will more coastal megacities due to population growth and increasing urbanization. Critical infrastructure, including dams, roads, bridges, ports, rail systems, and airports has been engineered and constructed to specifications based on the extremes observed under the climate of the past century. Significant infrastructure is concentrated in coastal zone areas that are particularly vulnerable to extreme weather and rising sea level. In areas of permafrost, where ground stability is threatened by warming, infrastructure such as pipelines is highly vulnerable. The vulnerability is especially clear in our defense and maritime shipping apparatus reliant upon coastal ports. More frequent and prevalent climate extremes in the coming decade imply that we will likely see both more frequent infrastructure failure and growing demand for financial resources to harden existing infrastructure.

Impact upon the Arctic, the global commons, and natural ecosystems: The global impact of climate change, as well as the impact on the Arctic region, the coastal zones, and critical ecological resources such as Amazonia, will increase competition and hopefully cooperation among nations to accommodate changes. This is clearly evident in the case of the Arctic Basin as it loses its summertime ice cover faster than expected, enabling new trade routes and expanded opportunities for oil and other mineral exploration.

The probability of a major storm crippling a megacity will increase because storms will become more destructive, surge from higher sea-levels, and there will be more megacities due to population growth and urbanization. The World Bank assessed the impact of climate change on three Asian coastal megacities (Bangkok, Ho Chi Minh City, and Manila) and concluded that all three faced significant risks (2-6% of regional GDP) due to increasing frequency of climate extremes. The day after Hurricane Sandy pounded New York City (October 30, 2012), Governor Andrew Cuomo stated, "We have a new reality when it comes to these weather patterns. We have an old infrastructure and we have old systems and that is not a good combination."

2. The National Security Context

Human security and the interests of nations are at stake as a result of the environmental changes we expect to see in the coming decades. The prospect of serious socioeconomic disruptions in response to weather and climate related extreme events is more imminent than previously thought – a cause for significant concern in the later part of this century, but affecting society in significant ways today and through the coming decade. The impact on human security and the individual will be profound as will the collective response of nations. The national security context will change. *(See page 13: Case Studies Linking Climate Stress and National Security.)*

Much of what we assume about the future based upon our experience with the past may be in doubt. Human population is projected to grow to 9.2 billion in 2050, an increase of more than 30% from the present. The increase over the 70 years from 1980-2050 will exceed the increase experienced during the 150,000 years prior to 1980. Economic activity per person has also grown substantially. The production and consumption of goods and services per capita grew by more than 70% between 1975 and 2010. While improvements in technology have enabled us to make more efficient use of resources, aggregate resource use has generally outstripped these efficiency gains due to larger, more affluent, populations. In addition, environmental pressures such as climate change will further stress the resource base required to sustain human development.

As a result, we must now seriously consider futures constrained by Earth's continuing capacity to provide the resources to support human society in context of social and environmental stressors. When and where we bump up against these constraints we will need to adapt. In some cases, these adaptations may be long anticipated, well planned, and orderly. In other situations, they may be forced by surprises, chaotic in implementation, and pose significant national security challenges. In some cases, adaptations will be carried out smoothly by self-organizing processes such as markets, but other cases will require interventions. Whenever the stakes are high, decision makers who already have robust assessments will hold a significant advantage.

This report focuses on the scientific basis for expecting an increase in the frequency and area affected by extreme weather over the next decade, with consideration of the physics that underlie the functions of global and regional climate. The conclusions will be controversial to some. But the evidence is inescapable that more frequent weather extremes are having impacts that concern our security interests today. The report warns that we can expect this to continue. The risk is sufficient to warrant attention. It is evident that human security and the interests of most nations are at stake. The impacts of climate changes affect society in significant ways today and through the coming decades. They pose complex questions regarding the human dimension – the response of people, individually and collectively, as their environment changes.

Recent years have witnessed a marked increase in concern that climate stress will pose significant challenges for U.S. national security. Such concern has been reflected in scientific scholarship, in publications of policy think tanks, and in high-level government publications such as the Quadrennial Defense Review. Behind this recent thinking about climate-security linkages is a combination of new understanding of the vulnerability of societies to climatic stress, underscored by a series of recent case examples that bring these vulnerabilities into sharp relief and a mounting empirical record that demonstrates that weather extremes are becoming more common. These linkages can be broadly categorized as: 1) multipliers of political instability threats; 2) interaction of climate stress and globalization; 3) disruption of international politics through changes in territory and diplomacy; and 4) drivers of humanitarian crises.

Multipliers of political instability threats: Political instability, in the form of coups, civil war, and other forms of internal political violence constitutes a major U.S. national security threat for which strong possible connections to climate stress have been identified. In the aftermath of the Cold War and the rise of major security problems linked to political instability in the early 1990s, major resources have been devoted to understanding the causes of political instability, with significant advances being made.

Several key drivers of instability have clear links to climate stress. For example, a prolonged drought in a poor, agriculturally dependent society will generate consequences:

- Depression of livelihoods among rural societies, as herding and farming yields decline
- Depression of government revenue, as agricultural exports decline
- Increased movement of populations in search of suitable pasture and cropland
- Decreased perceptions of government legitimacy, if responses to the crisis are judged inadequate.

Each of these consequences has been shown to elevate the risk of political instability. The same dynamics contribute to the risk of humanitarian emergencies. The genocide in Darfur was preceded by a multi-decade drought that generated such consequences. The recent collapse of the Mali state also was preceded by a severe drought linked to these consequences.

CASE STUDIES LINKING CLIMATE STRESS AND NATIONAL SECURITY

The following examples linking climate stress, society, and security foreshadow events that the world may face in the near future.

Northern Sahel. Drought fuels Tuareg rebellion and Islamic extremism.

Climate shocks in the 1970s and 1980s, coupled with corruption and discriminatory government policies, lead some Tuareg to migrate north where they were radicalized, armed, and trained by the Libyan regime. After the Gaddafi regime fell in 2011, these fighters returned to Mali, formed the National Movement for the Liberation of Azawad, declared independence, and collaborated with Islamic extremists with ties to Al Qaeda. A severe drought contributed to the breakdown in order, and the extremists toppled the Malian government and seized control of the north.

Pakistan. Strategically important country with high climate vulnerability.

Pakistan is extremely vulnerable to climate stress due to its physical geography and interacting demographic, socioeconomic, political, and institutional dimensions. It is exposed to multiple weather and climate extremes including cyclones, tornadoes, monsoons, glacial melt, floods, landslides, heat waves, and droughts. The failure to provide timely, coordinated, and adequate humanitarian relief to recent disasters has contributed to weakened security. Islamic extremist groups have taken advantage of these conditions to establish grassroots charities providing emergency care, food, shelter, and employment to disaster victims as a means of recruiting support for militant networks.

Indonesia. Amplified natural hazards and competition for resources.

Indonesia has always been vulnerable to stress from weather and climate extremes. The country is located in a region that makes it highly sensitive to El Niño-Southern Oscillation (ENSO) events. The large 1997-98 El Niño triggered a severe drought, massive fires, and crop loss that accentuated the Asian financial crisis and elevated pressure on the failing Suharto regime. Emerging changes in rainfall and storm patterns are affecting food security and coastal vulnerability. Large-scale biofuel production, to meet rapidly rising global demand, is generating conflict over land.

Russia. Food security, urban unrest, and stress on fragile international systems.

In 2010, decreased grain production in southern Russia and neighboring countries, stemming from high temperatures and reduced rainfall, led to a spike in global wheat prices. Russia banned exports as a reaction to domestic food security fears. This move put even greater upward pressure on food prices worldwide, with particularly acute shocks in regions dependent on wheat imports. Thus climate stress in Russia helped accentuate unrest in Egypt, Tunisia, and Algeria during early 2011.

Arctic. Loss of sea ice generates international tensions.

Arctic sea ice has experienced historical minima in recent years, with a transition to summer season ice-free status now well underway. This shift has put strain on an uneasy status quo regarding territorial competition in the region. Territorial and Exclusive Economic Zone (EEZ) boundaries are disputed in the region, and now that shipping and mineral exploration are suddenly more feasible these disputes are starting to escalate.

In any single case it is not possible to attribute causal responsibility for political instability to climate stress, but statistical tests can help identify the overall pattern. Published tests clearly demonstrate that deviations from normal climatic conditions are associated with a significant increase in the risk of political violence (see the box above). Although the strength of this proposition continues to be debated by scholars, there is no doubt that the evidence supports heightened attention to the linkages.

Interaction of climate stress and globalization: Political instability can also be exacerbated by climate stress that operates through less direct means. Globalization creates patterns of vulnerability that can be accentuated by climate shocks. The food price spikes of 2010, generated by severe drought in key global wheat producing regions in Eurasia, led to a sharp increase in dissatisfaction with political leadership in several Arab countries. The combination of an acute shortage of affordable food, deep-rooted concerns about legitimacy, and absence of mechanisms for peaceful political contestation help explain the emergence of the Arab Spring in 2011.

Another example of indirect transmission is in the area of policy responses. In 2008 and 2010, the worldwide diversion of crop production to biofuel contributed to sharp increases in global food prices. The biofuel surge is largely a result of climate policies mandating increased production. Similarly, concerns about water scarcity, in part elevated by worries over climate change but also prompted by economically driven increases in consumption, have led some countries to increase construction of reservoirs on transboundary rivers, or even in some cases to contemplate diversion that harms downstream interests. Such policy responses elevated cross-border tension in regions such as the Lancang-Mekong, Ganges-Brahmaputra, and Ili River (Kazakhstan-China) basins.

A third and key category of policy response that has raised alarms is the sharp increase in foreign land acquisitions. Several countries that are worried about their long-term ability to meet food security needs (driven again in part by climate change projections) have responded by executing long-term leases and purchases of agricultural land in poor countries. Because poor agrarian countries are often politically fragile, the injection of contentious land politics may be destabilizing. Indeed, the government of Madagascar fell in 2009 precisely because of a controversy over the government's handling of a major land deal with South Korea.

The vulnerabilities associated with globalization have the potential to transmit the impacts of weather and climate extremes to the U.S. homeland. The Thailand floods of 2011, triggered by a combination of unusually heavy rains and land use changes in the region, shut down production of key components for computer hard drives. This led to a global hard drive shortage that lasted for months. The heavy concentration of critical elements of the global supply chain in this vulnerable region could easily be repeated elsewhere. Another possible threat to the U.S. homeland lies in the shifting patterns of infectious disease that could be triggered by climate change. Dengue fever, for example, has shown signs of moving into the southern U.S. as habitat conditions for the Aedes aegypti mosquito shift. Similarly, Vibrio bacteria, a precursor to gastrointestinal diseases such as cholera, are now living in the Baltic Sea – a migration enabled by warmer waters.

Disruption of international politics through changes in territory and diplomacy: Finally, climate change has the potential to disrupt international politics in a way that creates national security problems for the U.S. Reductions in Arctic sea ice have already triggered fears of a scramble for control of shipping lanes and mineral deposits in the region. Competing territorial claims in the region had not been associated with international tension in the past, because there were no viable prospects for acting on such claims. As the Arctic has been free of ice in late summer to a greater extent and for longer periods than ever before, prospects for mineral exploitation, fisheries exploitation, and shipping are now much more real. The prospects for challenging conflicts over control are potent. A similar dynamic has emerged in the northern border between India and Pakistan. Unresolved territorial disputes are being exacerbated by fears that climate change is affecting transboundary water resources of the Himalayan glaciers and thus upsetting the fragile political equilibrium.

Weather and climate extremes may create degraded conditions that terrorist and criminal organizations could exploit to their advantage. The water crisis in Yemen, for example, though largely driven by growth in consumption in an arid region, has been augmented by rainfall shortages. This crisis has been linked to the weakness of the regime, which in turn has heightened concerns of a growing Al Qaeda presence. Similarly, in northern Mali there are fears that the loss of state control has created a potential haven for Al Qaeda and its sympathizers. The drought in Mali cannot be blamed as the primary force behind this development, but it clearly played a role in the history of contested control in the region. The collapse of the Somali state was exacerbated by long-term drought in the region, and has generated long-lasting security threats. These examples demonstrate that weather and climate extremes can influence hostile interests in new regions of the world.

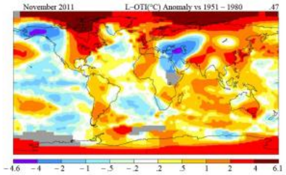
Drivers of humanitarian crises: Humanitarian crises with clear direct links to climatic stresses – disasters associated with droughts, floods, severe storms, temperature extremes, wildfires, and landslides – are growing rapidly. In addition, complex humanitarian emergencies arise through the interaction of multiple stresses, such as political violence, refugee flows, malnutrition, and epidemics. Often such crises emerge in places that constitute threats to U.S. national security because of the need to employ U.S. military resources as part of an organized response or because of destabilizing effects in critical regions.

During the 20th century, patterns of interdependence and vulnerability evolved in a way that led to a dramatic increase in the role of socioeconomic forces in shaping U.S. national security. These processes accelerated in the aftermath of the Cold War. Now the 21st century is shaping up to be a period in which weather and climate extremes are generating similar levels of security threats. Therefore, understanding the nature of these climatic stresses as they are likely to unfold in the near term is of crucial national security importance.

Heat Waves

Trend/Event. Recent heat waves and potential for more frequent heat waves in the future.

Description/Impact. The Berkeley Earth Surface Temperature group recently released results that confirm other previous work that indicates a temperature rise of 0.9°C has occurred already. Record highs now outpace record lows by 2 to 1. 40,000 people died as a result of Europe's record-breaking heat wave in 2003. The summer of 2003 was the hottest in 140 years. There is evidence that towards the end of this century, every summer in Europe could be as hot as the summer of 2003. It is very likely that heat-waves could become hotter in the future in London and that heat-related mortality could increase six-fold. This is also true for Boston, Budapest, Dallas, Lisbon, and Sydney.



Temperature Anomaly, 11/2011 (NASA)

National Security Implications. Extreme heat waves can cause a variety of impacts to a country's security, with ripples back to US security. Food price spikes after the 2010 Russian heat wave provide a good example. High temperatures can also impact a country's ability to operate power facilities reliant upon cooling water, such as France's shutdown of nuclear reactors during a 2009 heat wave.

Reference: NASA, 2011; Meehl, 2009; Muller/Berkeley Earth Surface Temperature group, 2011; Schiermeier in Nature, 2011; Gosling, 2011.

Drought

Trend/Event. Recent drought and potential for more frequent droughts in the future.

Extreme Drought Conditions

Description/Impact. Increasing temperatures and changes in precipitation create the potential for future drought conditions, with some regions experiencing persistent drought. One regional example of multiple recent droughts is the Horn of Africa, which recently experienced the worst drought that eastern Africa has suffered in 60 years. More than 11 million people needed food assistance, and the arid conditions caused famines in Somalia. Tens of thousands of people died. In 2010, a severe drought in Southeast Asia and southern China caused the Mekong River to drop to a 50-year low. In Peru, droughts associated with El Niño events in the 1980s and 1990s spurred increased migration from rural areas to cities.

National Security Implications. Increasing regional drought conditions impact regional and global food and water security. Lack of available water may also affect energy security in areas relying on water-intensive energy sources.

Reference: United Nations, 2011; Fraser in The Daily Climate; MercyCorps, 2011; Schearf in VOA, 2010; Tomas Castelazo, 2007.

Floods

Trend/Event. Recent floods and potential for more frequent floods in the future.

Description/Impact. Increasing water vapor in the atmosphere leads to greater precipitation amounts. This increase of precipitation for some areas leads to a greater chance of flooding, especially in developed areas where natural water flow has been altered. One example is the 2011 Thailand flooding that occurred during the monsoon season. The flooding inundated about 14.8 million acres of land, over 740,000 acres of which are farmland, in 58 provinces. It has been described as "the worst flooding yet in terms of the amount of water and people affected" Seven major industrial areas were inundated by as much as 10 feet. As of December 3, 2011, some areas still remained 6 feet underwater and many factory areas remained closed.

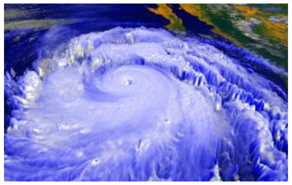
National Security Implications. Increased regional flooding destroys infrastructure and impacts local industry. Flooding in areas with existing instabilities or inadequate response capabilities may create security crises for countries of interest. The Thailand flood affected global supply chains for items like computer hard drives.

Thailand Floods, October 2011

Reference: US Navy & AFP, 2011.

Severe Storms

Trend/Event. Recent severe storms and potential for more intense storms in the future.



Potential for Increased Storm Intensity

Description/Impact. According to one study, the average intensity of tropical cyclones is expected to increase by 2-11% while the frequency of occurrence is expected to decrease by 6-34%. One example of repeated hurricane damage in a vulnerable area is Haiti, where the hurricane season of 2008 was the strongest they've ever experienced. Four storms--Fay, Gustav, Hanna, and Ike--dumped heavy rains on the impoverished nation. The rugged hillsides, stripped bare of 98% of their forest cover thanks to deforestation, let flood waters rampage into large areas of the country. Haiti suffered 793 killed, and the hurricanes destroyed 22,702 homes. About 800,000 people were affected. The flood wiped out 70% of Haiti's crops, resulting in dozens of deaths of children due to malnutrition in the months following the storms. Damage was estimated at over $1 billion, the costliest natural disaster in Haitian history.

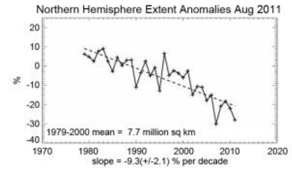
National Security Implications. The potential for increased storm intensity means greater risk for vulnerable populations living near coastal areas. Critical infrastructure may also be threatened, similar to the Gulf of Mexico oil facilities damaged during Hurricane Katrina.

Reference: Knutson et al., 2010; www.reliefweb.org; Masters, 2008; NASA, 2012.

Arctic Sea Ice

Trend/Event. Decreasing Arctic sea ice extent and thickness.

Description/Impact. The Arctic has experienced faster warming than the rest of the globe. The total volume of Arctic sea ice shrank last fall to the smallest amount ever observed during the age of satellites. The monthly averaged ice extent for August 2012 was 4.72 million square kilometers. This is 2.94 million square kilometers below the 1979 to 2000 average extent, and 640,000 square kilometers below the previous record low for August set in 2007. The Arctic has lost an area greater than all the U.S. states east of the Mississippi, and what ice remains appears to be getting thinner and weaker.



Decreasing Arctic Sea Ice Extent (NSIDC)

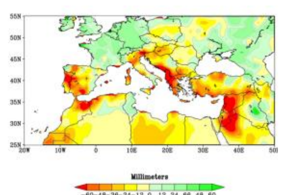
National Security Implications. The prospect of the disappearance of Arctic sea ice raises the risk of new rounds of competition, and injects uncertain elements to security, especially among the circumpolar states. The interrelations among the Arctic States involve sovereignty disputes, jurisdiction claims, resource competition, and military capacity expansion, while new non-Arctic interests in the Arctic draw in elements of international shipping, seabed resources exploitation, environmental concern, and scientific research.

Reference: NSIDC, 2011; O'Harra in Alaska Dispatch, 2011; University of Alberta, 2011.

Mediterranean Drought

Trend/Event. Recent drought in the Eastern Mediterranean may have contributed to Arab Spring uprisings. Some predictions for the future anticipate continued, persistent drought for this region. Rainfall in eastern Syria fell to 30 percent of the annual average in 2008, the worst drought for 40 years. The al-Khabour, a main tributary of the River Euphrates, dried up.

Description/Impact. In early 2011, food prices peaked at a level slightly higher than the peak level reached in 2008. Between 2006 and 2008 average world prices for rice rose by 217%, wheat by 136%, corn by 125%, and soybeans by 107%. Drought and oil price volatility were key drivers of the food price crisis in 2007 and 2008. In Syria, since the 2007/2008 agriculture season, nearly 75% of agriculture-dependent households suffered total crop failure. Just over 800,000 people have lost their entire livelihood, according to the UN and IFRC.



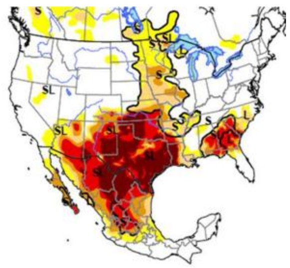
Decrease in Precipitation (1971 – 2010) (NOAA)

National Security Implications. This region is of critical interest to the US, especially the relationship between Israel and its regional neighbors. Government transitions in Egypt and issues over cross-border water rights hold much uncertainty. The current crisis in Syria remains tense. Continued stability in Iraq after US withdrawal is also a concern.

Reference: NOAA & UN, 2010; BBC, 2008; Erian *et al.*, 2010.

Mexico Drought

Trend/Event. The recent Mexico drought started in late 2010 and worsened throughout 2011, particularly across northern and central Mexico.



Mexico Drought, October 2011 (NADM)

Description/Impact. The area spanning the southwest U.S. and Mexico has experienced periods of prolonged drought in recent years, with expectation of transition to a state of persistent drying. By late October, more than half the country was in severe to exceptional drought, considered Mexico's worst drought in 70 years. Initial estimates: 2.5 million people affected, 2.2 million acres of cropland destroyed, and hundreds of thousands of livestock lost.

National Security Implications. Mexico has a weak central government, high crime, and major issues with drug cartels. Climate stresses have the potential to exacerbate tensions between the US and Mexico over illegal drug and gun trafficking as well as illegal immigration. This persistent drought may have a devastating impact on food, water, and energy in the region. This situation increases the risk of instability in Mexico. Heightened climate stress that affects local food security and water scarcity could further erode government power and contribute to deepening disorder.

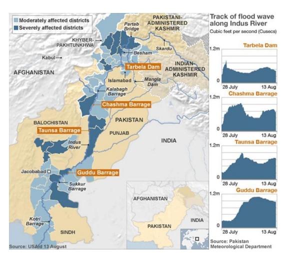
Reference: NOAA NCDC, 2011.

Pakistan Floods

Trend/Event. From late July to August 2010, rainfall related to the Asian monsoon was displaced unusually westward, and more than a foot of rain fell across a large area of the Upper Indus Valley. Flooding returned in 2011.

Description/Impact. The 2010 Pakistan floods covered at least 9.2 million acres, caused 2,000 casualties, displaced 20 million people, and washed out 70% of roads and bridges in affected areas. In the 2011 floods in Sindh, the infrastructure of health, education, and transportation was completely wiped out. Pakistan flooding in 2010 was connected to the Russian heat wave; an unusually strong polar jet stream shifted northward of Moscow and plunged south toward Pakistan, remaining in place for more than a month.

National Security Implications. Pakistan's stability is a key interest for the US, especially considering their influence with the conflict in Afghanistan, as well as operations against the Taliban and Al Qaeda in Pakistan. Pakistan's nuclear capability makes its level of stability a particular concern. Ongoing cross-border issues with India, including water transfer, add to the potential for climate to affect the status quo. In recent testimony, DNI Clapper mentioned the Pakistan floods were a military issue for the US.

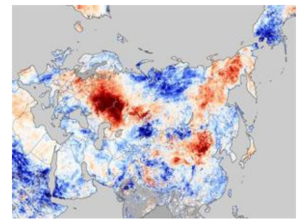


Pakistan Floods, 2010 (USAID)

Reference: DNI, 2011; NASA, 2011; NCDC, 2011; USAID, 2010; Houze et al., 2010.

Russian Heat Wave

Trend/Event. Record warm temperatures, drought, wildfires, and poor air quality impacted Russia during July 2010, continuing through mid-August across western Russia. The head of the Russian Meteorological Service said that the country experienced "the longest unprecedented heat wave for at least 1,000 years".



Russian Heat Wave July 20–27, 2010 (NASA)

Description/Impact. Unofficial estimates placed the death toll near 15,000 people across Russia, with 7,000 in Moscow alone. At the beginning of August, over 430,000 acres were burning with over 600 active fires. Outside Moscow, Russia's most deadly wildfire since 1972 charred homes and farmland. Economists predicted the heat and fire would cause over $15 billion in loss of economic growth this year.

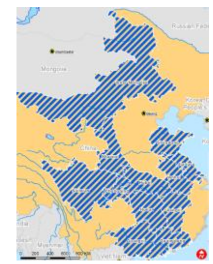
National Security Implications. A major impact from the fires and heat were the loss of wheat crops. Russia is the world's third-largest exporter of wheat and had recently slashed its harvest forecast from 90 million metric tons to 60 million metric tons. Due to the shortage, the 18 million metric tons that were to be exported would no longer leave the country—threatening wheat prices worldwide. Military and nuclear installations were also threatened across the country by the fires, prompting the emergency transport of missiles and nuclear fuels out of harm's way.

Reference: NOAA NCDC, 2010.

China: Drought & Floods

Trend/Event. The 2010 drought in southwestern China was referred to as the worst in a century. That same year, heavy rainfall and flooding in northeastern China led to the evacuation of more than 250,000 people in Dandong.

Description/Impact. By March, 2010, about 51 million people faced water shortages in a number of provinces. Fearing unrest due to soaring food prices, authorities sent 10,000 armed police to the affected regions. Three Gorges Dam power production was down by 20% as a result of this drought. The narrowing and shallowing of the Yangtze stranded thousands of boats and left a 220km stretch off limits for container ships. Droughts in 2011 destroyed grain that would have been enough for nearly 60 million Chinese to eat for a year.



2012 Flood-Affected Chinese Provinces

National Security Implications. China's economic growth and position of influence make it a key state of interest to the US. Climate stresses have the potential to disrupt China's flow of water, decrease their hydropower generation capability, impact food and water security, and affect internal stability. China's growth is driving them to expand their energy and food sources beyond their borders. China's military presence is also expanding to ensure the flow of these critical resources.

Reference: NOAA NCDC, 2011; ClimateWire, 2011; Watts in Guardian, 2011; Moore, 2010; Red Cross & Asia News, 2012.

3 Current Understanding of the Climate System

Increasing concentrations of greenhouse gases combined with changes in the concentration of particulate matter (aerosols) are responsible for important changes in regional and global climate. Until recently, the warming influence of greenhouse gases has been offset to a significant extent by cooling contributed by aerosols, most notably by sulfate particles formed by oxidation of sulfur dioxide released primarily in conjunction with combustion of coal. Steps taken in the US and Europe over the last few decades to reduce emissions of aerosols and their precursors have resulted in an important increase in the net positive radiative forcing of the climate system. Plans for China point in the same direction. Consequences include: accelerated warming of continental regions of the northern hemisphere, particularly at higher latitudes; a decrease in the ice cover of the Arctic Ocean, most notably in summer; a general slowdown of the polar jet, and the tendency of the jet to develop large-scale meanders, resulting in unusual patterns of persistent weather; and an expansion of the Hadley cell, resulting in a poleward extension of desert regions. All of these factors have been implicated in the general increase of weather extremes observed over the past decade.

The chapter begins, in Section 3.1, with an overview of the factors responsible for a changing global climate: increases in the concentration of greenhouse gases, changes in the influence of aerosols, and the role of a varying output of energy from the sun. Section 3.2 addresses recent data on the changing (increasing) heat content of the ocean, combined with trends in global and regional surface temperatures, with specific discussion of the impact of aerosols. Section 3.3 focuses on the implications for regional weather. Section 3.4 discusses internal (natural) factors contributing to varying weather conditions.

3.1 Earth's Temperature Response to Radiative Forcing

Radiative forcing is a process that either elevates or decreases Earth's temperature because of an imbalance between solar energy absorbed and infrared energy radiated back out into space (see box). Our level of understanding of this process, and our ability to model it, affects our understanding of weather and climate variability and trends and our ability to relate them to causative factors, such as human-induced greenhouse gas emissions. It also affects our ability to understand and predict security-relevant environmental changes that affect human society and actions. We recommend an effort to observe and assess changes and trends in radiative forcing.

RADIATIVE FORCING

"Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. The word radiative arises because these factors change the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. This radiative balance controls the Earth's surface temperature. The term forcing is used to indicate that Earth's radiative balance is being pushed away from its normal state."

"Radiative forcing is usually quantified as the 'rate of energy change per unit area of the globe as measured at the top of the atmo- sphere', and is expressed in units of 'Watts per square metre'. When radiative forcing from a factor or group of factors is evaluated as positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system." (From IPCC 4th Assessment: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf, FAQ 2.1 Box, p. 136.)

The concept of radiative forcing as employed by the Intergovernmental Panel on Climate Change (IPCC) (see box) and as used commonly in a variety of climate studies is relatively simple. It seeks to provide a rough estimate of the change in energy flux at the top of the atmosphere in response to an assumed change in atmospheric composition. In the case of a greenhouse gas such as CO_2, the composition is assumed to be constant as a function of altitude. The concept first calculates the change in the temperature of the stratosphere subject to an assumption that the temperature everywhere in the stratosphere adjusts to the new composition according to what is referred to as local radiative equilibrium. That is to say, at every level in the stratosphere and above, it assumes that there should be no net source of energy: sources and sinks of energy are taken to be in precise balance. The temperature of the lower atmosphere (the troposphere) and surface are fixed at levels that prevailed prior to the postulated change in composition. The resulting change in the flux of energy at the base of the stratosphere (the tropopause) is then calculated. Since there is no net source or sink for energy above the tropopause, the change in energy at the tropopause should be the same as the change in energy at the top of the atmosphere, an indication therefore of the resulting imbalance in global energy. The justification for this presumption (why temperatures in the stratosphere should be allowed to adjust while temperatures in the troposphere and at the surface are fixed) is based on two physical factors:

1. The stratosphere (closer to space) can adjust relatively rapidly to the compositional change
2. The temperature in the troposphere and at the surface will be controlled to a larger extent by the dynamics of the climate system, by prevailing conditions at the surface, and by the vagaries of the changing circulations of the atmosphere and ocean in response to the changing energetics of the global system.

Concerns relating to human-induced climate change have been based historically on two sources of information: evidence for a significant long-term increase in global average surface temperature, and the interpretation of these data using complex coupled ocean-atmosphere-cryosphere-biosphere models. The models are driven by computational estimates of imbalance in the global energy budget resulting from changes in solar irradiance and changes in the abundance of radiatively active constituents of the atmosphere. For example, an increase in the concentration of an infrared-absorbing gas such as CO_2 would mean that the region of the atmosphere from which radiation could escape to space would transition to a higher level of the atmosphere. Since temperature decreases with altitude in the relevant region, this would result in a reduction in the emission of infrared energy to space. The Earth would cool less. All other factors equal, this would result in a net gain of energy, triggering warming. This sequence defines the essence of the greenhouse effect and the source of the concern with respect to human-induced climate change.

Radiative forcing can also be negative. An increase in the abundance of light-colored particulate matter in the atmosphere (aerosols), or clouds, would be expected to enhance reflection of incident sunlight, contributing to an increase in the planetary albedo with a resulting decrease in the quantity of energy absorbed from the sun. This is the direct effect. Global temperatures would be driven to decline in this case, to reduce the emission of infrared energy to space as needed to restore global energy balance. IPCC distinguishes between the direct and indirect effects of aerosols. The latter account for the possibility that aerosols can serve as effective nuclei for condensation of atmospheric water vapor, contributing to a potential increase in the prevalence and reflectivity of clouds, thus resulting in additional negative radiative forcing.

Climate Sensitivity

Radiative forcing is usually identified as the response to a specified instantaneous change in atmospheric properties – doubling of CO_2, for example. There are two important aspects to this response. As discussed, we expect an increase in atmospheric temperature (assuming that the forcing is positive) as the system adjusts to accommodate the related additional net input of energy. The temperature of the atmosphere must increase, so that eventually the increase in radiation to space catches up with the assumed initial imbalance. This leads to a new equilibrium with a generally warmer planet. The increase in CO_2 and resulting warming triggers additional changes in the planetary heat budget. These changes can be either positive or negative. For example, an increase in the abundance of water vapor in the atmosphere would be expected to add to the warming caused by increased levels of CO_2 (water vapor is an important greenhouse agent). On the other hand, an increase in cloud cover, resulting in enhanced reflection of sunlight, would have the opposite effect. The equilibrium change in global temperature resulting from a specified forcing is expected to account for both the direct and

> A change in the concentration of greenhouse gases and/or aerosols may be expected to alter the balance between energy absorbed by the Earth from the sun and energy emitted back to space. The energy excess (or deficit) is reflected primarily through a change in the heat content of the ocean. The ocean has been gaining energy over the past fifty years, and arguably since the end of the 19th century, indicating that the energy imbalance has been generally positive – the Earth and its climate system has been adjusting to a persistent net increase in energy.

indirect effects of the forcing identified in terms of what is referred to as the climate sensitivity, S, defined by

$$S = (\Delta T)_{eq} \div F$$

where $(\Delta T)_{eq}$ defines the magnitude of the resulting equilibrium global average temperature change prompted by a specific change in net input energy F.

With $(\Delta T)_{eq}$ expressed in °C, and F given in units of watts per m^2 (Wm^{-2}) averaged over the Earth's surface, S has units of °C per watt per m^2. The classic study by Charney et al. (1979) estimated a value for S equivalent to 0.75°C $\pm$ 0.375°C per watt per m^2 of global surface area, which would imply that the global average temperature should increase by 3°C $\pm$ 1.5°C if the abundance of CO_2 were to double (equivalent to a radiative forcing of 4 Wm^{-2}). The models considered by IPCC cover a range of values for the temperature change resulting from a doubling of CO_2, from a low of 2.1°C to a high of 4.4°C corresponding to a range of values for S from 0.525°C per Wm^{-2} to 1.1°C per Wm^{-2}. A recent study by Hansen and Sato (2012) based on a consideration of paleo data extending back 800,000 years argues that the range of permissible values for S should be narrowed to 0.75°C $\pm$ 0.125°C per Wm^{-2}, which would imply an equilibrium temperature increase of 3°C $\pm$ 0.5°C for a doubling of CO_2.

The response of global temperature to a specific imposed radiative forcing depends not only on the value assumed for the climate sensitivity (S), but also on the temporal response to the imposed forcing. The additional energy absorbed by the Earth heats not only the atmosphere and surface, but will also heat the ocean. If the radiative forcing is negative, as expected to result from an increase in reflective aerosols, the entire system must adjust, in this case contributing to a decrease in atmospheric and surface temperatures with a corresponding decrease in the quantity of heat stored in the ocean. The greater the sensitivity of the climate system, the longer the time required to reach equilibrium. With higher sensitivity, a larger portion of the imposed energy imbalance must be shared not only with surface levels of the ocean, but also potentially with regions of the ocean at depth. The current generation of models suggests that perhaps 40% of the anticipated equilibrium temperature response can be realized in as little as five years. The subsequent response, however, may require as much as hundreds of years or longer. The GISS model discussed by Hansen et al. (2011) takes as much as 600 years to reach 80% of the eventual equilibrium temperature response. Results from other climate models are similarly sluggish. Hansen et al. (2011) concludes that the existing set of climate models generally overestimate the time required for the global system to respond to radiative forcing. The few models that do factor in deep oceans significantly overestimate the rate at which heat is transferred to the deep ocean, thus extending the time required for the surface to approach its new equilibrium value. A similar conclusion was reached earlier by Forest et al. (2006).

Solar Influences

The climate system is expected to respond not only to changes in the concentrations of greenhouse gases and aerosols, but also to changes in solar activity. The output of energy from the sun varies typically over a period of approximately 11 years (the so-called solar cycle). The energy crossing a unit surface area oriented perpendicular to the rays of the sun at (roughly) the average distance between the Earth and sun is referred to as the solar constant. Figure 1 summarizes data on the variation of the solar constant as measured over the past 35 years.

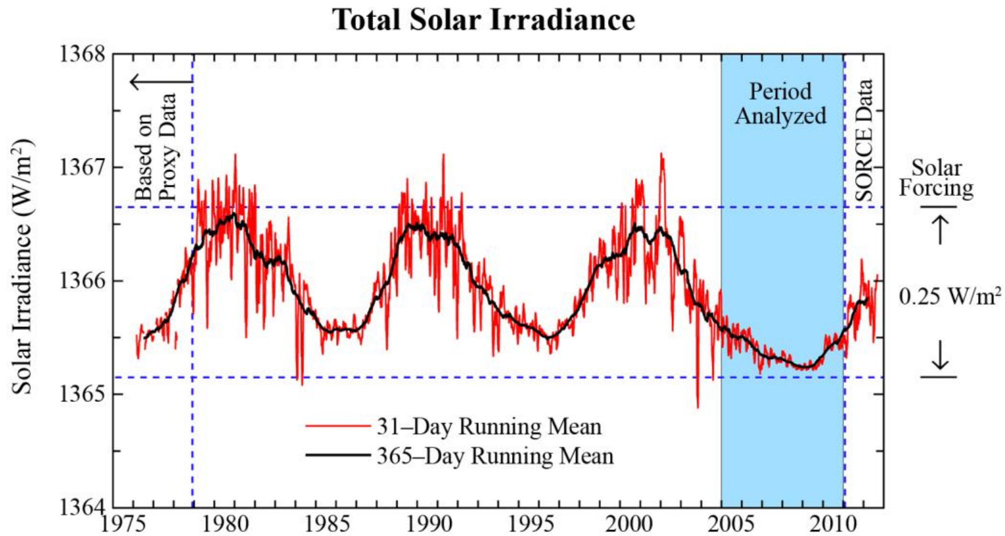


Figure 1. Solar Irradiance.

Solar irradiance from a composite of several satellite-measured time series. Monthly mean (red line) and annual mean (black line). Image from Hansen et al. (2011).

The results presented here cover a little more than three solar cycles including the most recent minimum, which lasted from about 2004 to 2010. As indicated, the most recent minimum was more persistent and the magnitude of the energy flux decreased to a level lower than was observed during either of the two prior solar cycles. The change in the magnitude of the solar constant from solar maximum to solar minimum amounts to about 1.5 W m$^{-2.}$ This implies a change over a solar cycle of a little more than 0.25 W m^{-2} in the rate at which solar energy is absorbed by the Earth (averaging over the planetary surface and accounting for energy reflected back to space). Hansen et al. (2011) argue that the decrease in solar irradiance between 2000 and 2009 was responsible for a reduction in energy input to the Earth of approximately 0.14 W m^{-2}. They suggested that this may have contributed to the relatively small change in surface temperatures observed over the same period as indicated by the data presented in Figure 4 and Figure 6. It is important to note, though, that despite the decrease in solar energy input, the heat content of the ocean continued to increase, as indicated in Figure 3. The sun is currently transitioning into a period of enhanced emission. To the extent that the recent reduction in solar luminosity contributed to a decrease in the rate of growth of surface temperatures, we can expect this trend to reverse in the next decade.

Performance of Climate Models

Climate models (usually coupled Atmosphere and Ocean Global Circulation Models) are typically tuned to reproduce past variations in global average surface temperature. Early studies restricting attention to the influence of the changing concentration of greenhouse gases had difficulty in reproducing the trend observed over the past 150 years. Models typically predicted an increase in global average temperature greater than what was actually observed. This was followed by a recognition that aerosols could provide a source of negative radiative forcing, offsetting the forcing contributed by the combination of greenhouse gases and aerosols. Given the uncertainty in specifying the magnitude and time history of the contribution of aerosols to overall radiative forcing, it is clear that the introduction of a potential aerosol influence provided models with an important additional degree of freedom. This facilitated efforts to fit the historical global surface temperature data. Stott and Forest (2007) summarize the values assumed for aerosol forcing in the models employed to simulate climate for purposes of the IPCC (2001, 2007), ranging from a high negative value of -1.1 Wm^{-2} to a low of -0.4 Wm^{-2}.

Close inspection of a number of the models employed by IPCC indicates that while the models are generally successful in reproducing past trends in global average surface temperature, details of the climates simulated by these models can vary significantly from model to model. Differences include important variations in the simulations of regional climate, in addition to significant differences in treatments of the hydrological cycle – greater or lesser rainfall, greater or lesser cloud cover, differences in cloud altitudes and thicknesses, etc. Under these circumstances, the ability of models to project conditions in the next decade is questionable. There is a view, however, that useful information can be obtained by combining results from a range of models (an ensemble). The argument in this case is that errors will tend to cancel when outputs from a range of models are combined, so that results from an ensemble of models are likely to be more credible and robust than results from any single model.

Responding to the conclusion that the incorporation of excess heat in the ocean by the current generation of models is excessive, Hansen et al. (2011) explored the implication of potentially faster responses of the climate system to extraneous sources of radiative forcing. If the climate system is assumed to respond faster to radiative forcing than rates assumed in the current generation of models, and if the models are still required to reproduce the changes in global average temperature observed over the past 150 years, it is clear that values for radiative forcing assumed by the models must be reduced. Since the contribution of greenhouse gases to radiative forcing is relatively well determined, this must require an increase in the magnitude of the negative forcing attributed to aerosols. To accommodate faster responses, it was necessary to increase the efficiency of the negative forcing attributed to aerosols (to reduce the net positive forcing contributed by the combination of aerosols and greenhouse gases). Hansen et al. (2011) concluded that in order to accommodate the faster climate responses envisioned in their intermediate and fast models, the magnitudes of the negative forcing attributed to aerosols should be increased by 33% and 66% respectively relative to the standard slow response simulation.

DID WARMING STOP IN 1998?

Recent controversy over the significance of human-induced climate change has focused on the lack of a significant change in global average temperatures over the most recent decade, since about 1998 (see Figure 6). An op-ed published in the Wall Street Journal by 16 distinguished scientists on January 27, 2012, challenged the credibility of the Intergovernmental Panel on Climate Change (IPCC) and the prevailing wisdom that “nearly all scientists demand that something dramatic be done to stop global warming”. They concluded that “the most inconvenient fact is the lack of global warming for well over 10 years”. A group of 38 climate scientists, many, if not all, associated with prior IPCC reports, responded that “climate experts know that the long-term warming trend has not abated in the past decade. In fact, it was the warmest decade on record”. How can we reconcile these discordant views? There are a number of points to make:

1. Intrinsic factors, essentially the noise of the climate system, can result in decade-long intervals over which global average temperatures exhibit little change. The longer, 150-year record indicates a number of occasions identified with hiati similar to that observed recently (Figure 2).
2. The case can be made (Kaufmann et al., 2011) that the minimal change in global average temperatures observed over the recent past can be attributed to the combination of an increase in negative forcing of the climate system responding to an increase in aerosols, prevalence of the cold (La Niña) ENSO phase (Figure 13), and the decrease in solar insolation associated with the extended recent solar minimum.
3. While global average surface temperatures may have varied little over the recent past, it is notable that 1998 was a warm El Niño year which may skew the averages. The evidence suggests significant changes in the geographic distribution of surface temperatures (Figure 7 and Figure 8) and in the heat content of the ocean (Figure 3).
4. An important, though unresolved, question concerns the potential significance of the interplay between natural variability as exemplified by these various fluctuations and human-induced change in regulating at least the short-term expression of the global climate system.

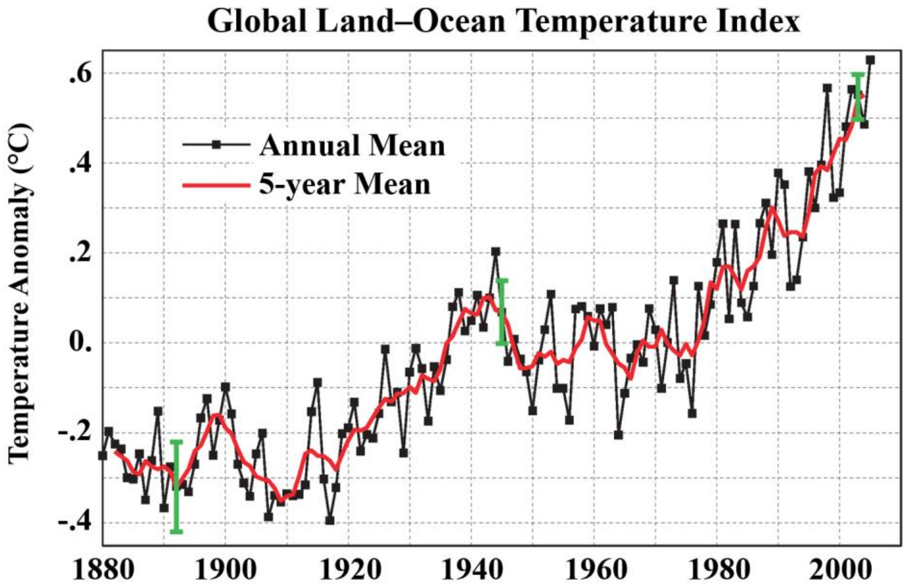


Figure 2. Global Land-Ocean Temperature Index.

Line plot of global mean land-ocean temperature index, 1880 to present, with the base period 1951-1980. The black line is the annual mean and the solid red line is the five-year mean. The green bars show uncertainty estimates. (Hansen et al., 2006).

3.2 Radiative Imbalance: Evidence from the Ocean, Land, and Atmosphere

If the trends in surface temperatures displayed above can be interpreted as persuasive evidence of a change in global climate, data from the ocean provide even more convincing evidence that the energy budget of the earth is no longer in balance. Without question, the planet is now gaining energy: energy absorbed from the sun indisputably exceeds that returned to space in the form of infrared radiation. The increase in heat content of the ocean clearly attests to this fact. It has been going on for at least the past 50 years, arguably much longer, and most likely since as far back as 1890.

There has been an impressive increase in measurements of the heat content of the ocean (an indication of total stored energy) over the past several decades attributed largely to the success of the international Argo float program. The Argo program employs a series of drifting robotic probes, deployed essentially worldwide. They are designed to record ocean temperature and salinity to depths as great as 2,000 m, although more realistically to about 1,750 m. The probes surface every 10 days, relaying their data by satellite to receiving stations around the world. The information is made available without restriction to the global community of ocean scientists. Some 3,500 of these probes were deployed and operational as of March, 2012.

A summary of data on ocean heat content reported by Trenberth and Fasullo (2012), essentially an update of results presented by Levitus et al. (2012), is displayed in Figure 3. A notable feature of this presentation is the recent increase in the heat content of the ocean at depth (below 700 m) as compared to the more muted change observed at shallower levels (above 700 m). In order to make easier comparisons, the numbers below have averaged the heat content change over the total surface of the Earth for the period of time of the observations. In this way, it is possible to convert very large numbers of joules to more manageable watts per meter squared. Stated thus, the rate of increase in ocean heat content to the lowest levels sampled by Argo averaged about 0.6 Wm^{-2} between 1993 and 2011. Hansen et al. (2011) adopted a value of 0.51 Wm^{-2} (again globally averaged) for the interval 2005 to 2010, with an uncertainty of 0.12 Wm^{-2} attributed to differences in treatments of the ocean data. They associated a somewhat higher value (0.625 Wm^{-2} with a similar uncertainty range) with the more extended period 1993 – 2008, consistent with the modest decrease in the growth rate of the ocean heat content observed most recently (Levitus et al., 2012). The decrease in solar luminosity during the most recent solar minimum may have contributed, as suggested by Hansen et al (2011), to the slowdown in heat uptake by upper levels of the ocean (above 700 m) since 2004 as indicated by the data in Figure 3. Recent reanalysis of data from the British Challenger expedition (1872-1876) (Roemmich et al., 2012) suggests that the heat content of the ocean may have increased by as much as a factor of 2 over the past 135 years with approximately half of the increase taking place prior to the 1950's. The obvious conclusion: the Earth has been out of energy balance for much of the past century, consistent with the trend in global average surface temperatures indicated in Figure 2.

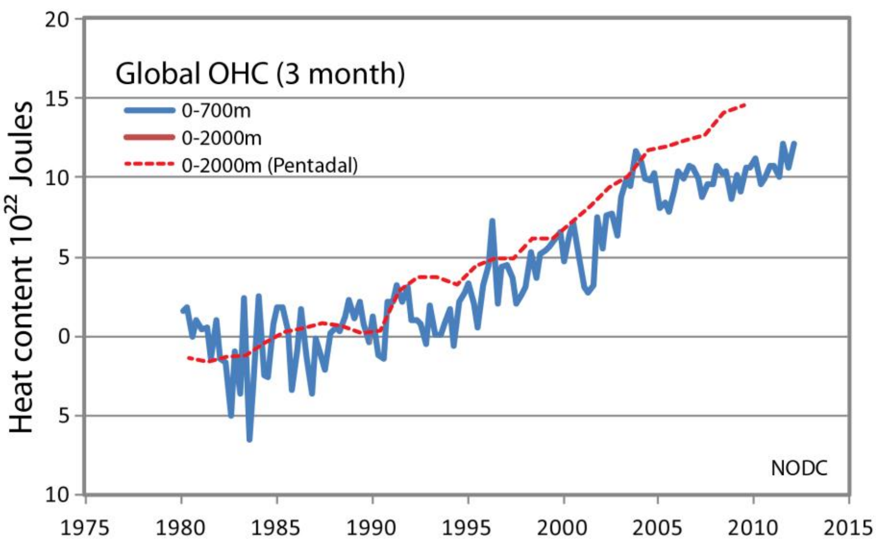


Figure 3. The Global Ocean Heat Content in 10^{22} J from NODC (NESDIS, NOAA), Updated from Levitus et al. (2012).

The blue and dark red curves show 3-monthly values for 0-700m (blue) and 0-2,000 m (dark red). The dashed red curve is the pentadal (running 5 year) analysis for 0-2,000 m for which, in the 1980s, the 2 standard deviation error is about $\pm 2\times10^{22}$ J, decreasing to $\pm 1\times10^{22}$ J in the early 1990s, but increasing in the late1990s until it decreases substantially to about $\pm 0.5\times10^{22}$ J in the Argo era. The reference period is 1955–2006. (Source: Trenberth, 2012).

The impact of warming has been significantly reduced, at least over the past 50 years or so, by an important offset contributed by negative forcing attributed to aerosols.

Considering constraints imposed by existing ocean heat content data, and accounting for additional storage of heat by the atmosphere and land as well as changes associated with the cryosphere, Hansen et al. (2011) concluded that aerosols should account for radiative forcing equivalent to -1.6 Wm^{-2} in 2010 with a subjective estimate of uncertainty of $\pm$0.3 Wm^{-2}. Murphy et al. (2009), in an independent analysis using space based measurements from the Earth Radiation Budget Experiment System (ERBE) and the Clouds and the Earth's Radiant Energy System (CERES), along with ocean heat content data, concluded that the aerosol forcing in 2000 would have amounted to about -1.8 Wm^{-2}, with an average of -1.1 $\pm$ 0.3 Wm^{-2} inferred for the period 1970 to 2000. Both conclusions are consistent with Hansen et al. (2011). These studies suggest that the impact of warming due to the increasing concentration of greenhouse gases has been significantly reduced, at least over the past 50 years or so, by an important offset contributed by negative forcing attributed to aerosols.

Our understanding of the physical and chemical properties of aerosols, including the details of their imputed impact on climate, is regrettably limited. Anthropogenic sources encompass a variety of forms of particulate matter produced by emissions of SO_2, NO_x, and NH_3, together with a range of species of organic carbon including black carbon or soot. Natural sources involve a variety of different forms of wind-blown dust including but not limited to light-colored particles raised by windstorms in desert regions (a source of negative radiative forcing). The relatively large negative values inferred by Murphy et al. (2009) and Hansen et al. (2011) for radiative forcing by aerosols suggest that the dominant impact of aerosols should be attributed to their role as a source of cloud nuclei, what IPCC defines as the indirect effect. This conclusion is consistent with recent analyses by Booth et al. (2012) and Leibensperger et al. (2012).

Aerosols are not well-mixed in the atmosphere. Though an unsettled scientific issue, the large variations in regional concentrations of aerosols are thought to influence local weather. For example, Booth et al. (2012) argue that changing patterns of sulfur emissions (including emissions associated with volcanoes) may have played a role in determining the variability of the Atlantic sea surface temperature (an index of the Atlantic Multidecadal Oscillation (AMO) (see box below)) at least over the past century. These sea surface temperature changes influence the phase of weather patterns from the North Atlantic to the Mediterranean. Others argue in favor of the influence of the ocean currents on the sea surface temperature. For example, the persistence of the variability observed over the longer interval covered by Knudsen et al. (2012) argues in favor of the ocean connection. Arguably both influences: changing patterns of aerosols and changing ocean currents may have played a role in affecting Atlantic sea surface temperatures over the more recent period. Leibensperger et al. (2012) argue for a major aerosol role in regional temperatures, concluding that trends in emissions of anthropogenic aerosols from the US over the period 1980 to 2010 had an important influence on climate over the Eastern US and the North Atlantic. Annually averaged temperatures over the central and eastern US declined by between 0.5 and 1.0°C between 1950 and 1990, in contrast to the significant increase in temperatures observed both globally and hemispherically particularly over the post 1970 period as indicated in Figure 4.

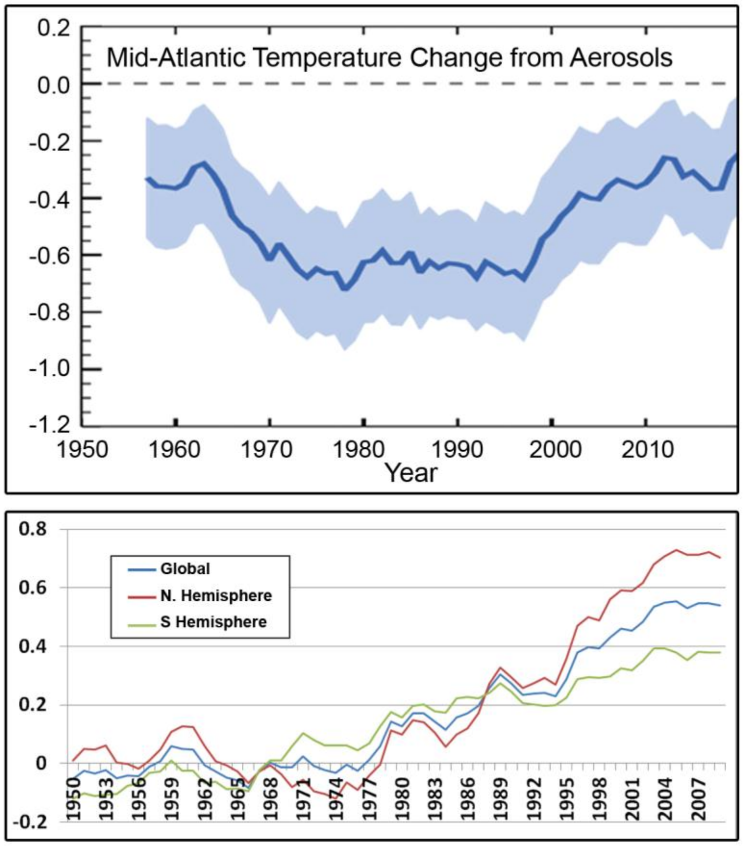


Figure 4. Eastern U.S. Cooling from Aerosols and Global Temperature Increases by Hemisphere.

Top graph: Change in annual mean surface air temperature (°C) over the mid-Atlantic U.S. due to U.S. anthropogenic aerosol sources. The time series has been smoothed with a 15-yr moving average. Shading indicates the 95% confidence interval (Leibensperger et al., 2012). Bottom graph: Global surface temperature change (°C, 5-year mean) (data from Hansen et al., 2010).

Leibensperger et al. (2012) attributed the warming over the eastern U.S. since 1995 to measures implemented in the U.S. to reduce emissions, notably of conventional pollutants and specifically SO_2 and NO_x. Sources for these pollutants peaked in 1980 and 1990 respectively (Figure 5). The results for global emissions presented here differ somewhat from those displayed in Figure 11. The more recent analysis is probably more accurate, although still subject to considerable uncertainty.

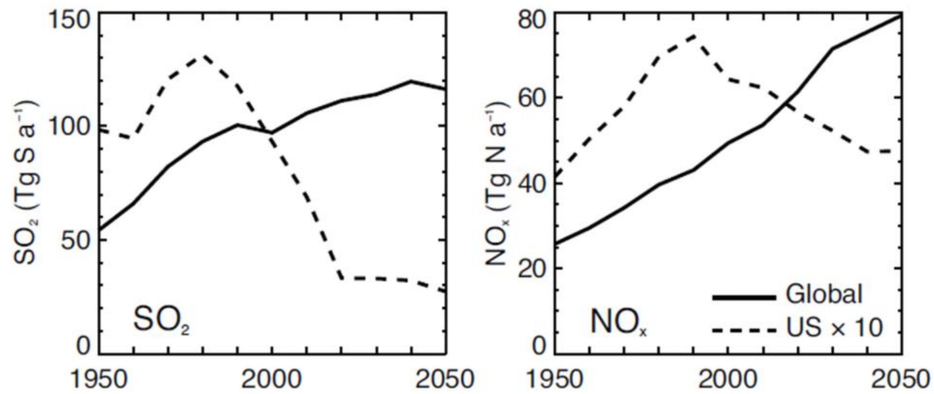


Figure 5. Global (solid) and U.S. (dashed) Trends in Emissions of SO_2, NO_x for 1950–2050.

US emissions are multiplied by 10 to fit on scale. SO_2 and NO_x emissions are from EDGAR (van Aardenne et al., 2001; Olivier and Berdowski, 2001). Emissions are extended past the year 2000 following the IPCC A1B scenario (Leibensperger et al., 2012).

They concluded that the negative radiative forcing attributed to anthropogenic aerosols originating from the U.S. declined by as much as 1.8 Wm^{-2} between 1990 and 2010. Measures taken over the same time interval to limit emissions in Europe would have resulted in an additional increase in net positive radiative forcing in the Atlantic sector (due to the further reduction in theoffsetting negative forcing from aerosols).

A plausible case can be made that the recent increase in net (positive) radiative forcing inferred for the North Atlantic environment may have largely contributed to the important recent changes in climate over extensive regions of the northern hemisphere, particularly at mid and high latitude regimes. Continuing efforts to limit emissions of pollutants implicated in causing damage to public health and to the general environment will further reduce the role of aerosols as an offset to the positive radiative forcing contributed by greenhouse gases.) We might thus expect the trends in climate recorded over the past decade to persist, indeed to become even more extreme, as we discuss below.

Figure 6 illustrates the differences between the trends in marine and terrestrial (sea vs. land) globally averaged surface temperatures over the past half century.

A notable feature of the results displayed here is the increase in land temperatures as compared to ocean temperatures over the past 15 years. This is exactly what one would expect from the recent increase in net positive radiative forcing resulting from the decrease in emissions of conventional pollutants discussed above. The impact of the resulting warming should be experienced first on land and later in the ocean, reflecting the higher heat capacity of the latter. Temperatures increased more rapidly at northern mid-latitudes than at southern mid-latitudes (Figure 7), a result again consistent with what one might expect if the increase in radiative forcing were experienced primarily in the north. (The bulk of anthropogenic emissions originate from industrial regions concentrated in the northern hemisphere). Wallace et al. (2012) concluded that a significant fraction of the excess warming observed from 1965 to 2000 was associated with dynamically induced warming in winter over high-latitude northern hemisphere continents.

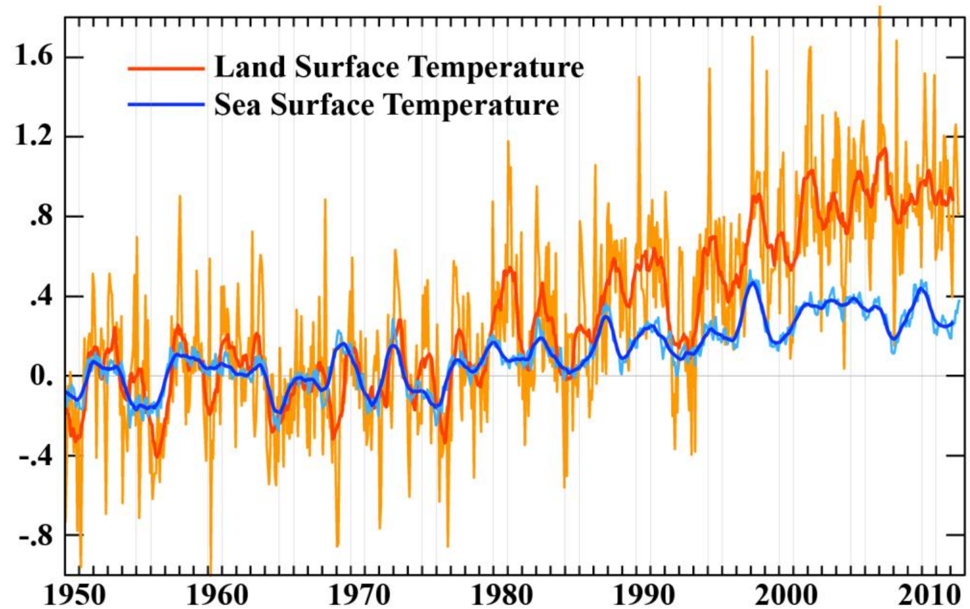


Figure 6. Monthly (thin lines) and 12-month Running Mean (thick lines) Global Land and Sea Surface Temperature Anomalies.

Base period is 1951-1980. Image from NASA/GISS.

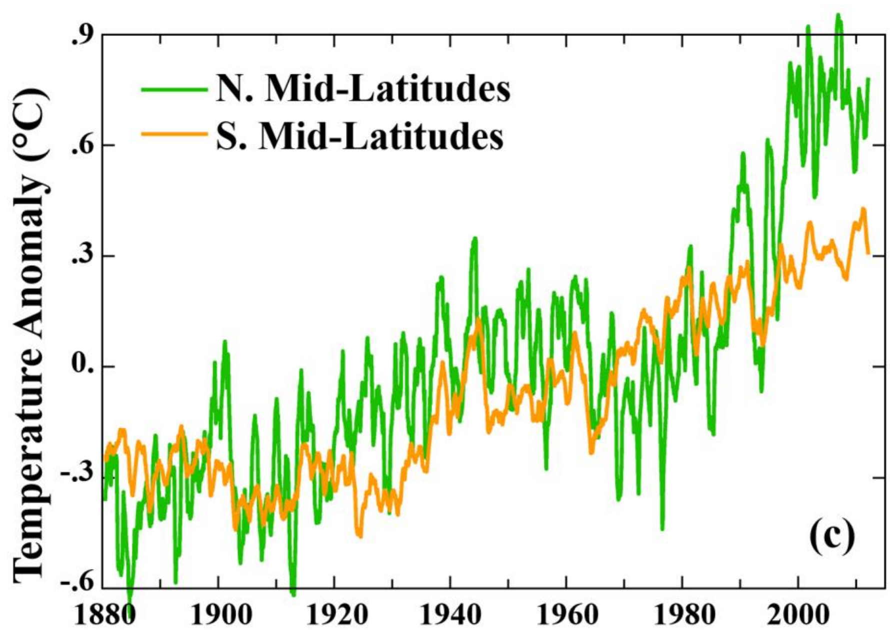


Figure 7. Temperature Change for Mid-Latitude Bands (12-month running mean).

N. Mid-Latitudes (64.2 - 23.6°N), S. Mid-Latitudes (23.6 - 64.2°S). Image from NASA/GISS.

In addition to the land-ocean difference, warming was strongest in the Arctic (Figure 8). This contributed to a notable decrease in summer ice cover in the Arctic Ocean, accompanied by an important decrease in multi-year ice in this region as illustrated in Figure 9.

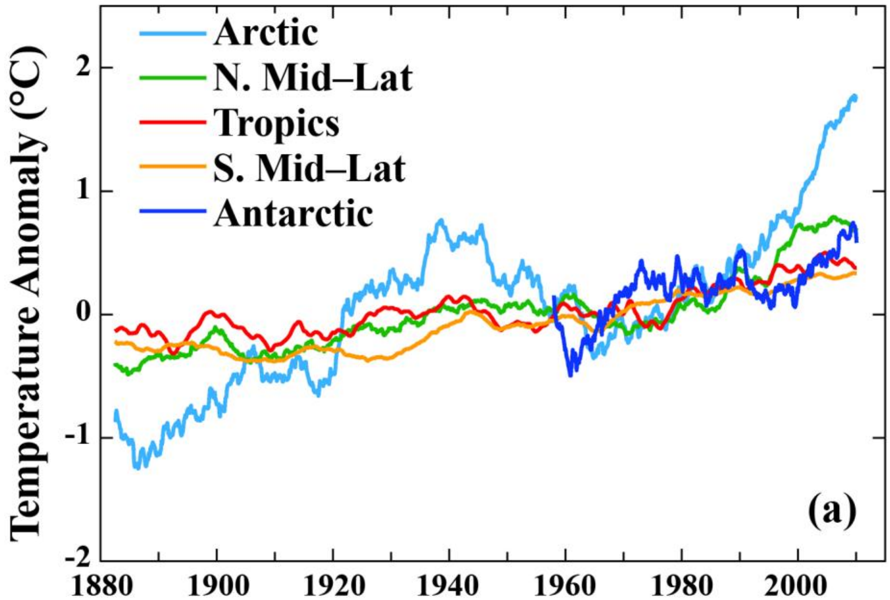


Figure 8. 60-month Running Mean Temperature Changes in Five Zones.

Arctic (90.0 - 64.2°N), N. Mid-Latitudes (64.2 - 23.6°N), Tropical (23.6°S), S. Mid-Latitudes (23.6 - 64.2°S), and Antarctic (64.2 - 90.0°S) (NASA/GISS).

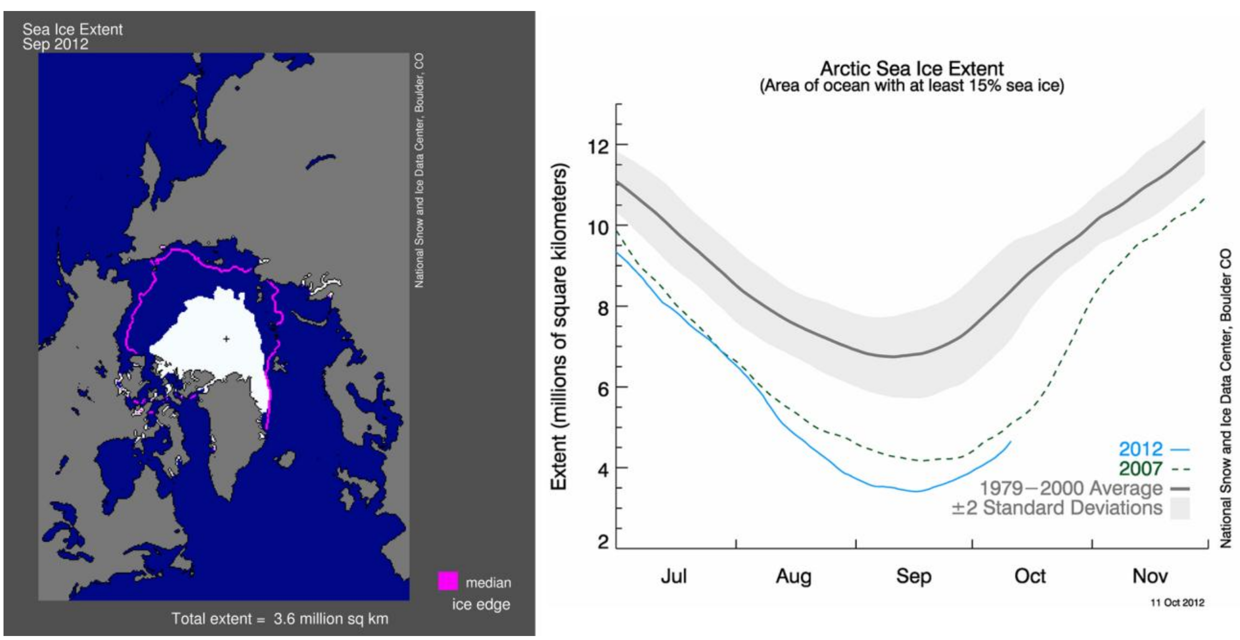


Figure 9. Arctic Sea Ice Reductions.

Left image: Orange line indicates 1979 to 2000 average extent for the day shown. White area (passive microwave satellite data) shows the total area of ocean covered with at least 15% ice in 2011. Right image: Recent changes in the spatial extent of sea ice in the Arctic Ocean; comparison of data for 2007 and 2012 with the average for 1979-2000. The ice-free regions during the late summers of 2007 and 2012 expanded by close to 3 million km^2 (roughly 30% of the entire land area of the US including Alaska) with respect to the long-term average. Images from National Snow and Ice Data Center.

3.3 The Impact of Changing Climate on Weather Systems

Arctic Amplification

> It is expected that large-scale circulation patterns throughout the northern hemisphere will become increasingly influenced by the fact that temperatures are increasing more rapidly at the poles than in the tropics – in the northern hemisphere this phenomena is known as Arctic Amplification

An extensive region of the U.S. east of the Rockies was bathed in tropical or sub-tropical air for much of the winter of 2012, resulting in what we refer to in this report as the year without a U.S. winter. Temperatures in Chicago were in excess of 80°F for an extended period in mid-March, a condition without precedent. Record high temperatures occurred over extensive regions of the eastern U.S. reflecting the favorable (warm side) location of this portion of the country with respect to the average position of the jet.

The question arises as to whether there has been an impact of greenhouse gases (GHG) warming on this kind of extreme event. Francis and Vavrus (2012) have carried out a diagnostic study showing that the decline in the strength of the polar jet defining the boundary between the mid-latitude and polar regimes is consistent with the decrease in the overall gradient of temperature between mid and high latitudes (Arctic Amplification – see box). (The larger the temperature gradient, the greater the speed of the wind required to balance the related gradient in pressure.) A possible further consequence would be an increase in the amplitude of the north-south (Rossby) waves associated with the jet. Think of the jet as developing large north-south meanders as it progresses slowly zonally around the planet, although the actual links here still need to be better understood. Figure 10 illustrates the latitudinal excursion of the jet observed on March 21, 2012. Liu et al. (2012) have demonstrated a link between the decrease in autumn Arctic sea ice and the winter Northern hemisphere circulation that appears to be related to other natural variability, namely the negative phase of the winter Arctic Oscillation (see box on page 39). This circulation change results in more blocking patterns and cold surges over northern continents, as well as bringing more moisture from the Arctic to produce snowfall in Europe and the U.S. In any case, Arctic warming results from Rossby wave propagation from lower latitudes, amplified somewhat by sea ice loss and perhaps by loss of snow cover earlier in the year. In short, the Arctic warming is a consequence of changes in lower latitudes. While it is possible that it feeds back on lower latitudes, it remains to be seen whether it has a substantial effect on the rest of the globe. To this we would add that as the offsetting effect of the aerosol induced cooling diminishes, the importance of the greenhouse gas warming can only increase.

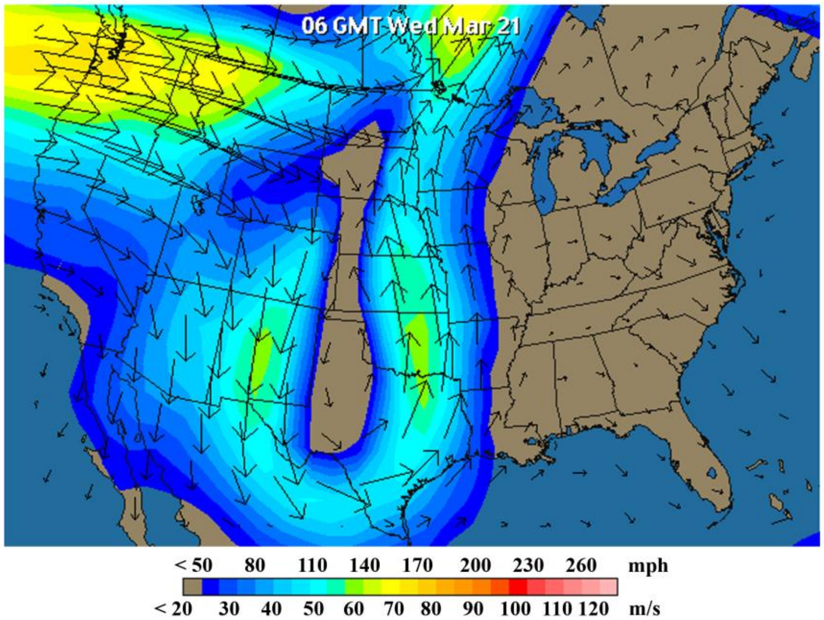


Figure 10. Path of the Jet Stream on March 21, 2012.

Image courtesy of wunderground.com.

Regional Influences of Aerosols

Emissions of SO_2, displayed in Figure 11, offer a useful surrogate for the trend over time in the global source of (anthropogenic) aerosols available to offset warming resulting from the increasing concentration of greenhouse gases. A breakdown of individual contributions to these emissions is displayed in Figure 12. The rapid increase in global emissions from about 1950 to 1970 offers a potential explanation for the pause (hiatus) observed over this time interval in the otherwise inexorable rise in global average surface temperatures.

Global emissions peaked in the early 1970's, reflecting primarily policy measures implemented in the US and Europe to minimize the environmental damage associated with acid rain (see Figure 12 for the temporal trend in US emissions). The increase in global average surface temperatures resumed subsequently. Emissions from China and from shipping (Figure 12) now constitute the most important, most rapidly growing sources of sulfur emissions, responsible in combination for the modest increase in the global source indicated for the post-2000 period in Figure 11. There are reasons to believe, though, that Chinese emissions may have decreased more recently as the government moves aggressively to deal with problems of local and regional (conventional) air pollution. As discussed by Lu et al. (2012), emissions from the US have decreased precipitously over the past 4 years, reflecting price-induced switching of fuels from coal to natural gas in the power sector, prompted by the recent fall in prices for natural gas, leading to selective idling of the most inefficient (oldest) coal-fired power plants that were generally not equipped to remove sulfur. As noted above, the recent downward trend in emissions from China and the US raises the possibility for a significant increase in net radiative forcing in the immediate future: in fact we may already be experiencing the impact of this increase.

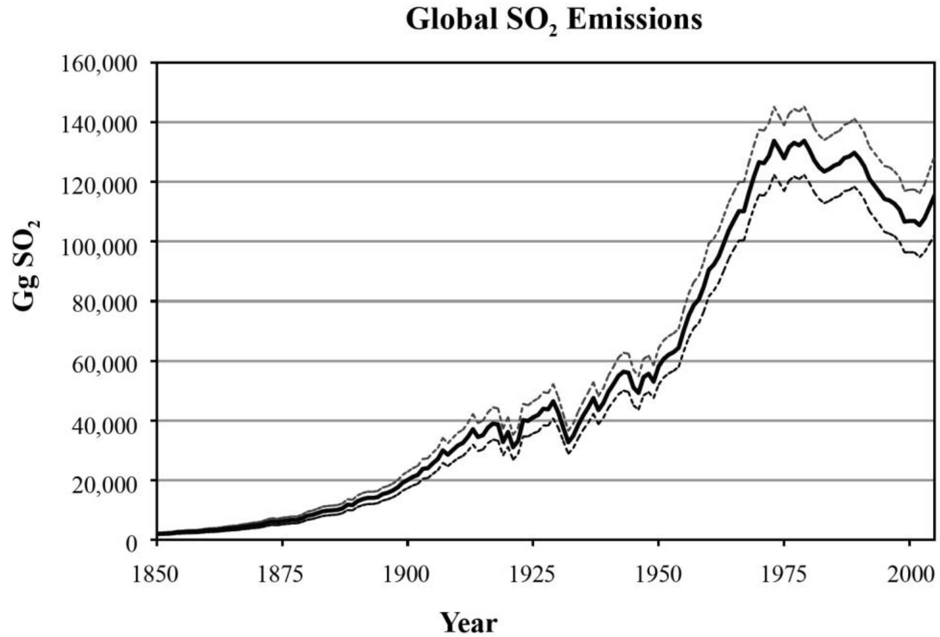


Figure 11. Global Sulfur Dioxide Emissions from Fuel Combustion and Process Emissions with Central Value (solid line) and Upper and Lower Uncertainty Bounds (dotted lines).

Source: S. J. Smith et al., 2011.

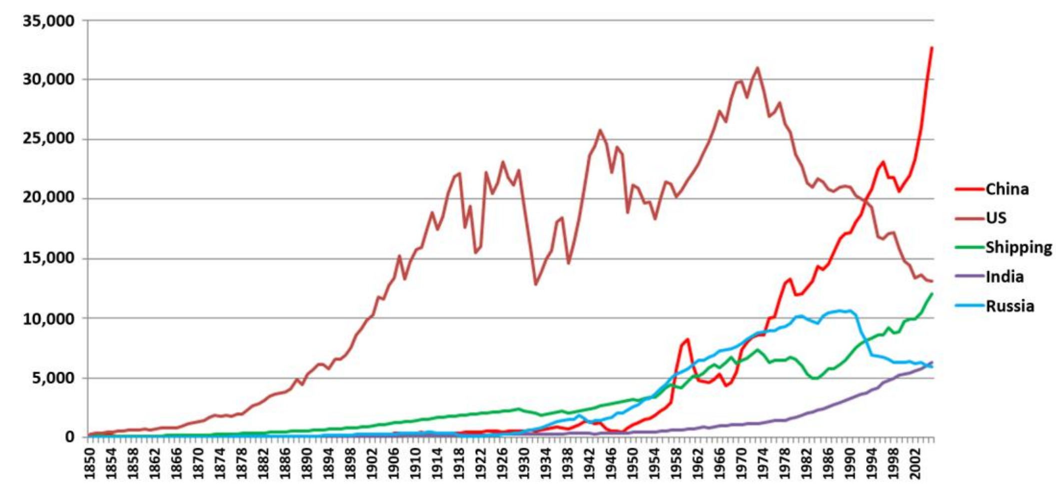


Figure 12. Top 5 SO_2 Emitters (Gg SO_2).

Data from Smith (2011).

A notable feature of the data presented in Figure 12 is the increase in emissions of sulfur associated with the use of high-sulfur bunker fuels by shipping. Emissions from this source likely surpassed those from the US at some point the early 2000's. It may be worth noting that emissions of sulfur (and nitrogen) into a relatively pristine environment (the atmosphere over the oceans) could have a differentially greater impact on climate as compared with emissions into more polluted environments closer to industrial sources. Emissions in the former case are more likely to contribute to production of the fine particles that could serve as an enhanced source of nuclei for condensation of water in clouds (more cloud particles, enhanced cloud reflectivity).

Authorities in Europe and in the U.S. are committed to legislating significant reductions in emissions of SO_2 from shipping, at least in their territorial waters. Prospects over the next decade or so are thus for an overall decrease in global emissions of sulfur, good news for public health, for a reduction in the acidity of precipitation, and for the overall health of the biosphere. The downside is that warming of the planet may accelerate and weather patterns may become increasingly anomalous.

Effect on Precipitation and the Hydrological Cycle

The rate of global precipitation is controlled ultimately by the rate of global evaporation, mainly from the ocean. The Argo float data (Levitus et al., 2012) confirm that the supply of heat to the ocean has been increasing over the past several decades. A significant fraction of the energy absorbed by the ocean is used to evaporate water. It would be reasonable, in light of the evidence for increased input of heat to the ocean, to expect a rise in evaporation. However, given the strength of the overall hydrological cycle, the resulting change might not be consequential (readily detectable). A conservative approach would be to assume that there has been little change in either global evaporation or precipitation over the recent past, and that this condition is likely to persist into the future. The atmosphere is warmer now than it has been in the past, and it has been observed that the abundance of water vapor in the atmosphere has increased, and it is likely to continue to do so. When conditions favor precipitation (rising atmospheric motion associated with the onset of a storm), it is probable that the intensity of the resulting rain or snowfall will increase as a consequence of the enhanced supply of water vapor. Of course, what really matters is the intensity and spatial distribution of that rainfall, which is controlled ultimately by dynamical processes in the atmosphere. If global precipitation is conserved, however, this means that it must rain or snow less in other regions or at other times. What we may expect, then, is weather whose patterns are more variable and generally more extreme - increased incidences of floods in some regions with droughts in others. This is precisely the pattern observed over the past several years as discussed later in this report. And the trend is likely to persist, indeed to become even more extreme, in the years ahead.

Impact on Extreme Conditions

> With a warmer climate, we may expect an expansion of what is known as the Hadley circulation, the system that dominates meteorological conditions in the tropics and sub-tropics. A poleward shift of the Hadley circulation system could cause these desert regions to extend to higher latitudes: think of the Sahara Desert extending across the Mediterranean into southern Europe or the southwestern desert of the U.S. moving north into the grain-producing region of the country.

A related question concerns the implications of a warming climate for violent storms – for hurricanes, major cyclones, and tornadoes for example. Emanuel (2007) has argued that there is no reason to expect an increase in the number of hurricanes (or typhoons, as these storms are called in the Pacific). However, he states that it is likely that these storms, feeding off higher sea surface temperatures, will be more energetic in the future, packing a stronger punch. A similar conclusion holds for major cyclones. Exposed to higher surface temperatures and an enhanced supply of water vapor (condensation of water vapor represents the primary energy source for hurricanes and major cyclones) these storms are expected to exact an increasing toll in the future, not only in damage to property but also in loss of life. On the other hand, despite public perception that tornadoes have become more frequent and more damaging recently and that they may have expanded their range, the scientific evidence supporting this view is at best ambiguous. There is no basis, therefore, in the case of tornadoes to offer any meaningful projections for the future.

With a warmer climate, we may expect an expansion of what is known as the Hadley circulation, the system that dominates meteorological conditions in the tropics and sub-tropics. Moisture laden air rises in the equatorial region. After losing the bulk of its moisture due to precipitation, the air moves to higher latitudes in the upper troposphere in both hemispheres, defining the upper branches of a matched pair of circulation loops. It sinks to the surface in the sub-tropics (in both hemispheres) at latitudes between about 25 and 35 degrees, returning to the equatorial source region through the lower branches of the circulation loops (defined by the trade winds). There is observational evidence for expansion of the Hadley cell by as much as 2 degrees of latitude between 1979 and 2005 (Fu et al., 2006; Seidel and Randel, 2007). There are also convincing theoretical reasons to attribute this expansion to an increase in temperature and moisture in the tropics (Held, 2000; Held and Soden, 2006; Lu et al., 2007; Frierson et al., 2007). It is interesting to note that models tend to greatly underestimate the observed expansion of the Hadley cell. There are two possible interpretations of this disparity. Much of the observed trend in the past 30 years could be a reflection of potentially reversible natural variability. Alternatively, it is conceivable that the models are underestimating the sensitivity of the mean meridional circulations to the buildup of greenhouse gases.

When the air sinks to the surface in the sub-tropics, it has already lost the bulk of its moisture. It is not only very hot in this case (in the absence of moisture the temperature of the air increases by close to 9°C for every kilometer of descent) but also very dry. The major desert regions of the world are generally co-located with the descending loops of the Hadley circulation system. A poleward shift of the Hadley circulation system would cause these desert regions to extend to higher latitudes: think of the Sahara Desert extending across the Mediterranean into southern

Europe, or the southwestern desert of the U.S. moving north into the grain-producing region of the country.

We may anticipate that expansion of the Hadley cell is likely to continue over the next several decades, largely as a consequence of the increase in the concentration of the greenhouse gases. We would not, however, expect the behavior of the Hadley circulation to be particularly sensitive to changes in emissions of the anthropogenic aerosols. The impact of those aerosols would be expressed more directly at higher latitudes of the northern hemisphere, although there could be an indirect influence if the aerosols prompted a larger scale change in ocean circulation that extended into the tropics.

3.4 Natural Variability in the Climate System

In addition to the longer-term impact of human induced changes in greenhouse gases and aerosols, the climate system may be expected to respond to a range of influences that may be considered natural in origin, variability reflecting the essential non-linearity of the underlying physics. Changes may arise on a variety of time scales, ranging from days or months in the case of weather to years or even hundreds of years in response to changes in the ocean. Examples of some of the more persistent changes affecting climatic conditions in the tropics and over large regions of the northern hemisphere include the El Niño –Southern Oscillation (ENSO), the Madden Julian Oscillation (MJO), the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and the Pacific Decadal Oscillation (PDO), with similar quasi-regular fluctuations observed in the southern hemisphere (see box). An interesting unresolved question concerns the potential significance of the interplay between natural variability as exemplified by these various fluctuations and human induced change in regulating at least the short-term expression of the global climate system.

The ocean-atmosphere system is closely coupled. As a consequence, the atmosphere is expected to respond to changing conditions in the ocean (specifically changes in the distribution of temperature expressed at the ocean surface), and vice versa. The El Niño – Southern Oscillation (ENSO) represents an important example of this variability, one that has been intensively studied in recent years. The extremes of this phenomenon are referred to as El Niño and La Niña. El Niño is identified with unusually warm conditions in the tropical Pacific extending from the dateline to the coast of South America. It is associated with drought over Indonesia, Australia, and southern Africa, and with unusually heavy rains over Peru and Ecuador. Meteorological conditions during La Niña reflect roughly a mirror image of those observed during El Niño (heavy rains over Indonesia, Australia, and South Africa; drought over Peru and Equator). ENSO also affects weather patterns over extensive regions of the tropics and sub-tropics, in environments as disparate as coastal California, the American Southwest, and northeast Brazil.

NATURAL OSCILLATIONS:
INTERANNUAL TO DECADAL FEATURES OF THE CLIMATE SYSTEM

In addition to the quasi-steady patterns of atmospheric circulation such as the trade winds and the Hadley cell, there are transitory patterns that can persist for weeks, months, and years. These patterns are called modes or oscillations, but they are only quasi-periodic. The patterns or oscillations are driven by changes in sea surface temperature and atmospheric pressure that arise from natural variability and are shaped by the ocean's ability to store and transport heat, as well the effects of soil moisture, vegetation, and snow and ice.

Because the patterns help determine the paths of big weather systems and thus the distribution of heat, rainfall, and ice, they can lead to variations in how wet, dry, warm, or cold a particular spot on Earth will be at any time of year. Over the years, there have been at least a dozen different oscillations identified and followed with increasing insight. Important oscillations discussed in this report include (by time scale):

- **Madden-Julian Oscillation (MJO):** irregular tropical disturbance of winds and rainfall that travels eastward with a cycle of roughly 30 to 60 days.
- **Monsoon:** a major tropical wind system driven by differential heating of ocean and land that reverses direction twice yearly, leading to wet (summer) and dry (winter) seasons. Major monsoonal circulations occur in Asia and India, although smaller monsoons are also found in equatorial Africa, northern Australia, and the southwestern U.S.
- **El Niño/Southern Oscillation (ENSO):** characterized by changes in tropical Pacific Ocean sea surface temperature and associated disruption of trade winds, rainfall and droughts. Both warm (El Nino) and cold (La Nina) events occur on an irregular cycle, with a warm event (El Nino) occurring about every four years.
- **Indian Ocean Dipole (IOD):** characterized by changing Indian Ocean sea surface temperatures that shift the normal convective winds to the west, leading to anomalous rainfall and droughts. Occurs on an irregular cycle of roughly 3 to 7 years.
- **Pacific Decadal Oscillation (PDO):** characterized by sea surface temperature shifts over the entire Pacific Ocean area, with largest impact on the jet stream across North America and fishery ecosystems in the Northeastern Pacific. Changes appear on a time frame of 15 to 30 years.
- **North Atlantic Oscillation (NAO):** the dominant mode of winter variability in this region characterized by an oscillation in atmospheric mass between the subtropical high and the polar low, reflecting the strength of westerly winds across the Atlantic into Europe. The index varies from year to year, but also can remain in one phase for several years. Related to the Arctic Oscillation, observed in the circumpolar Arctic.
- **Atlantic Multi-decadal Oscillation (AMO):** characterized by changes in the averaged North Atlantic sea surface temperature between the equator and 60 degrees north and associated with changes in the latitudinal overturning circulation. The cycle of warm and cool periods is multidecadal.

The warm phase (El Niño) is associated typically with unusually heavy rainfall over coastal California. The cold phase (La Niña) is implicated with abnormally dry conditions in the American southwest. The La Niña condition, which has applied over the past several years, as indicated in Figure 13, may have been responsible, at least in part, for the devastating, persistent drought experienced recently in Texas and extensively more recently (June 2012) over New Mexico, Utah, Nevada, and Arizona. Expansion of the Hadley circulation may also have played a role in this context, underscoring an important point: the potential significance of the interplay between natural variability and human induced change in regulating at least the short-term behavior of the global climate system.

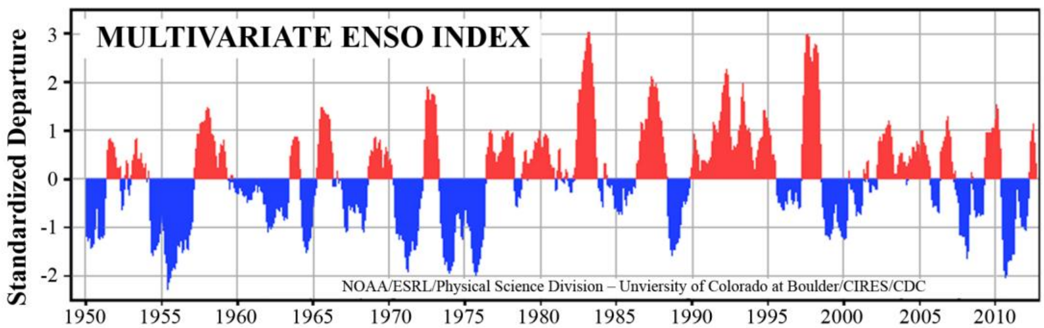


Figure 13. ENSO Index.

The Multivariate ENSO Index (MEI) illustrates periods of El Nino (red) and La Nina (blue). The index is based on the six main observed variables over the tropical Pacific. These six variables are: sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky. The MEI is computed separately for each of twelve sliding bi-monthly seasons (Dec/Jan, Jan/Feb, and Nov/Dec). Image from NOAA/ESRL.

Muller et al. (2012) concluded that the decadal variability of global land surface temperatures over the past 60 years is correlated significantly (correlation coefficient of 0.65) with the variability of the Atlantic sea surface temperature, as represented by the AMO index (Atlantic Multidecadal Oscillation). As noted in the box above, the AMO is associated with a more or less coherent pattern of variability of sea-surface temperatures in the North Atlantic. Monthly values for the departure of the AMO from the mean are displayed for the interval 1856-2009 in Figure 14, showing a variation on a time scale of between 60 and 90 years. As noted earlier, Booth et al. (2012) have argued that changing patterns of sulfur emissions may also have played a role in the AMO variability, at least over the past century. Knudsen et al. (2011) present evidence that the AMO has been a persistent feature of north Atlantic climate variability for at least the past 8,000 years. They point to a series of studies linking the AMO to changes in precipitation over North America, droughts in the Sahel, variability in northeastern Brazil rainfall, the frequency and intensity of tropical hurricanes, and potentially even to changes in the interhemispheric transport of heat.

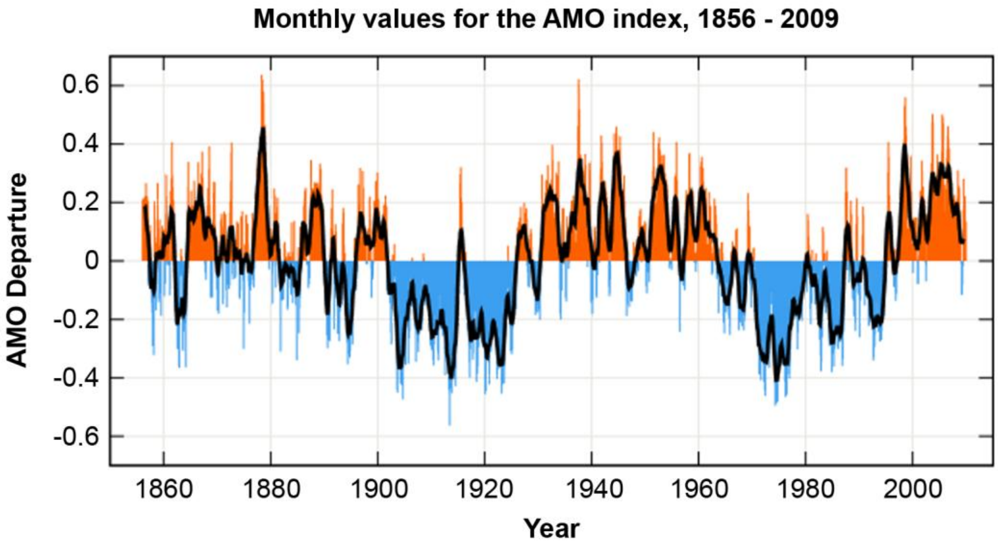


Figure 14. Monthly Values for the AMO Index 1856 – 2009.

The timeseries are calculated from the Kaplan sea surface temperature (SST) dataset which is updated monthly. It is an index of the North Atlantic temperatures. NOAA ESRL creates both a smoothed and unsmoothed version. Image from Wikipedia, Data from NOAA ESRL.

3.5 References

Arkin, P. A., Smith, T. M., Sapiano, M. R. P., & Janowiak, J. (2010); The Observed Sensitivity of the Global Hydrological Cycle to Changes in Surface Temperature, Environmental Research Letters, 5(3), 035201. doi:10.1088/1748-9326/5/3/035201.

Booth, B., Dunstone, N. J., Halloran, P. R., Andrews, T., and Bellouin, N. (2012); Aerosols Implicated as a Prime Driver of Twentieth-century North Atlantic Climate Variability, Nature, doi:10.1038.

Charney, J. G., Arakawa, A., Baker, D., Bolin, B., Dickenson, R., Goody, R., Leith, C., Stommel, H., and Wunsch, C.; Carbon Dioxide and Climate: A Scientific Assessment, Natl. Acad. Sci. Press, Washington DC, USA, 33 pp., 1979.

Emanuel K. A., 2007; Environmental Factors Affecting Tropical Cyclone Power Dissipation, Journal of Climate. 20:5497-5509, DOI: 10.1175/2007JCLI1571.1.

Enfield, D. B., Mestas-Nunez, A. M. & Trimble, P. J.; The Atlantic Multidecadal Oscillation and its Relationship to Rainfall and River Flows in the Continental U.S., Geophys. Res. Lett. 28, 2077–2080 (2001).

Folland, C. K., Colman, A. W., Rowell, D. P. & Davey, M. K.; Predictability of Northeast Brazil Rainfall and Real-time Forecast Skill, 1987–1998. J. Clim. 14, 1937–1958 (2001).

Folland, C. K., Parker, D. E. & Palmer, T. N.; Sahel Rainfall and Worldwide Sea Temperatures, Nature 320, 602–607 (1986).

Forest, C. E., Stone, P. H., and Sokolov, A. P.; Estimated PDFs of Climate System Properties Including Natural and Anthropogenic Forcings, Geophys. Res. Lett., 33, L01705, doi:10.1029/2005GL023977, 2006.

Francis, J. A., and S. J. Vavrus (2012); Evidence Linking Arctic Amplification to Extreme Weather in Mid-latitudes, Geophys. Res. Lett., 39, L06801, doi:10.1029/2012GL051000.

Frierson, D. M. W., J. Lu, and G. Chen (2007); Width of the Hadley Cell in Simple and Comprehensive General Circulation Models, Geophys. Res. Lett., 34, L18804, doi:10.1029/2007GL031115.

Fu, Q., Johanson, C. M., Wallace, J. M., and Reichler, T.; Enhanced Mid-Latitude Tropospheric Warming in Satellite Measurements, Science 26 May 2006: Vol. 312. no. 5777, p. 1179, DOI: 10.1126/science.1125566.

Goldenberg, S. B., Landsea, C. W., Mestas-Nunez, A. M. & Gray, W. M.; The Recent Increase in Atlantic Hurricane Activity: Causes and Implications, Science 293, 474–479 (2001).

Hansen J., Sato, M., Kharecha, P., and von Schuckmann, K.; Earth’s Energy Imbalance and Implications, Atmos. Chem. Phys., 11, 13421–13449, 2011.

Hansen, J. and Sato M.; Paleoclimate Implications for Human-made Climate Change, in Climate Change: Inferences from Paleoclimate and Regional Aspects, edited by: Berger, A., Mesinger, F., and Sijacki, D., Springer, in press, 350 pp., 2012.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade, 2006; Global Temperature Change, Proc. Natl. Acad. Sci., 103, 14288-14293, doi:10.1073/pnas.0606291103.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010; Global Surface Temperature Change, Rev. Geophys., 48, RG4004, doi:10.1029/2010RG000345, data downloaded from http://data.giss.nasa.gov/gistemp/graphs_v3/.

Held, I. M. (2000); The General Circulation of the Atmosphere, paper presented at 2000 Woods Hole Oceanographic Institute Geophysical Fluid Dynamics Program, Woods Hole Oceanogr. Inst., Woods Hole, Mass.

Held, I. M., and B. J. Soden (2006); Robust Responses of the Hydrological Cycle to Global Warming, J. Clim., 19, 5686– 5699.

Hu, Q. & Feng, F.; Variation of the North American Summer Monsoon Regimes and the Atlantic Multidecadal Oscillation, J. Climate 21, 2371–2383 (2008).

Intergovernmental Panel on Climate Change (IPCC), Climate Change 2001; The Scientific Basis, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, UK, 881 pp., 2001.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007; The Physical Science Basis, Solomon, S., Dahe, Q., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L.: Cambridge Univ. Press, 996 pp., 2007.

Kaufmann R. K., Kauppi H., Mann M. L., Stock J. H. (2011); Reconciling Anthropogenic Climate Change with Observed Temperature 1998–2008, Proceedings of the National Academy of Sciences (July 5). doi: 10.1073/pnas.1102467108.

Kerr, R. A.; A North Atlantic Climate Pacemaker for the Centuries, Science 288, 1984–1985 (2000).

Knudsen, M. F., Seidenkrantz, M. S., Holm Jacobsen, B., and Kuijpers, A.; Tracking the Atlantic Multidecadal Oscillation through the Last 8,000 Years, Nature Communication, 2, Article number: 178, doi:10.1038/ncomms1186, 2011.

Leibensperger, E. M., Mickley, L. J., Jacob, D. J., Chen, W.-T., Seinfeld, J. H., Nenes, A., Adams, P. J., Streets, D. G., Kumar, N., and Rind, D.; Climatic Effects of 1950–2050 Changes in U..S Anthropogenic Aerosols – Part 2: Climate response, Atmos. Chem. Phys., 12, 3349–3362, doi:10.5194/acp-12-3333-2012, 2012.

Leibensperger, E. M., Mickley, L. J., Jacob, D. J., Chen, W.-T., Seinfeld, J. H., Nenes, A., Adams, P. J., Streets, D. G., Kumar, N., and Rind, D.; Climatic Effects of 1950–2050 Changes in U.S. Anthropogenic Aerosols – Part 1: Aerosol Trends and Radiative Forcing, Atmos. Chem. Phys., 12, 3333–3348, doi:10.5194/acp-12-3333-2012, 2012.

Levitus, S., Antonov, J. I., Boyer, T. P., Baranov, O. K., Garcia, H. E., Locarnini, R. A., Mishonov, A. V., Reagan, J. R., Seidov, D., Yarosh, E. S., and Zweng, M. M. (2012); World Ocean Heat Content and Thermosteric Sea Level Change (0–2000 m), 1955–2010, Geophys. Res. Lett., 39, L10603, doi:10.1029/2012GL051106.

Liu, C., & Allan, R. P. (2012); Multisatellite Observed rRsponses of Precipitation and its Extremes to Interannual Climate Variability, Journal of Geophysical Research, 117(D3), 1-16. doi:10.1029/2011JD016568.

Lu, J., G. A. Vecchi, and T. Reichler (2007); Expansion of the Hadley Cell under Global Warming, Geophys. Res. Lett., 34, L06805, doi:10.1029/2006GL028443.

Muller, R. A., Curry, J., Groom, D., Jacobsen, R., Perlmutter, S., Rohde, R., Rosenfeld, A., Wickham, C., and Wurtele, J.; Decadal Variations in the Global Atmospheric Land Temperatures, Berkeley Earth Surface Temperature Study, 2012, available online at http://berkeleyearth.org/results-summary/

Murphy, D. M., Solomon, S., Portmann, R. W., Rosenlof, K. H., Forster, P. M., and Wong, T.; An Observationally Based Energy Balance for the Earth since 1950, J. Geophys. Res., 114, D17107, doi:10.1029/2009JD012105, 2009.

NASA Goddard Institute for Space Studies, New York, NY; GISS Surface Temperature Analysis, online at http://data.giss.nasa.gov/gistemp/graphs_v3/.

National Snow and Ice Data Center; Arctic Sea Ice News and Analysis, online at http://nsidc.org/arcticseaicenews/.

NOAA Earth System Research Laboratory; AMO (Atlantic Multidecadal Oscillation) Index, online at http://www.esrl.noaa.gov/psd/data/timeseries/AMO/.

NOAA Earth System Research Laboratory; Multivariate ENSO Index (MEI), online at http://www.esrl.noaa.gov/psd/enso/mei/.

Olivier, J. G. J. and Berdowski, J. J. M.; Global Emissions Sources and Sinks, in: The Climate System, edited by: Berdowski, J., Guicherit, R., and Heij, B. J., A. A. Balkema Publishers/Swets and Zeitliner Publishers, Lisse, The Netherlands, 33–78, 2001.

Qiang Fu, Celeste M. Johanson, John M. Wallace, Thomas Reichler; Enhanced Mid-Latitude Tropospheric Warming in Satellite Measurements, Science 26 May 2006: Vol. 312. no. 5777, p. 1179, DOI: 10.1126/science.1125566.

Seidel, D. J., and W. J. Randel (2007); Recent Widening of the Tropical Belt: Evidence from Tropopause Observations, J. Geophys. Res., 112, D20113, doi:10.1029/2007JD008861.

Smith, S. J., van Aardenne, J., Klimont, Z., Andres, R. J., Volkej A., and Delgado Arias, S., (2011); Anthropogenic Sulfur Dioxide Emissions: 1850–2005, Atmospheric Chemistry and Physics, 11:1101–1116, data downloaded from http://beta.sedac.ciesin.columbia.edu/mva/so2emissions/.

Smith, T. M., Sapiano, M. R. P., & Arkin, P. A. (2008); Historical Reconstruction of Monthly Oceanic Precipitation (1900–2006), Journal of Geophysical Research, 113(D17), 1-18. doi:10.1029/2008JD009851.

Stott, P. A. and Forest, C. E.; Ensemble Climate Predictions Using Climate Models and Observational Constraints, Phil. Trans. R. Soc. A, 365, 2029–2052, 2007.

Sutton, R. T. & Hodson, D. L. R.; Atlantic Ocean Forcing of North American and European Summer Climate, Science 309, 115–118 (2005).

Trenberth, K., personal communication, 2012.

van Aardenne, J., Dentener, F., and Olivier, J.; A 1×1 Resolution Data Set of Historical Anthropogenic Trace Gas Emissions for the Period 1890–1990, Global Biogeochem. Cy., 15, 909–928, 2001.

Wallace, J. M., Fu, Q., Smoliak, B. V. Lin, P., and Johanson, C. M.; Simulated Versus Observed Patterns of Warming over the Extratropical Northern Hemisphere Continents during the Cold Season; PNAS, 2012.

Weather Underground; Arctic Warming is Altering Weather Patterns, Study Shows, online at http://www.climatecentral.org/news/arctic-warming-is-altering-weather-patterns-study-shows/.

Wikipedia; Atlantic Multidecadal Oscillation, online at http://en.wikipedia.org/wiki/Atlantic_multidecadal_oscillation.

4 Current Observations

A review of the observational record demonstrates that the prevalence of recent climate extremes exceeds historical expectations and that their extent is worldwide, affecting people where they live, where they draw upon fresh water resources, and where they grow food.

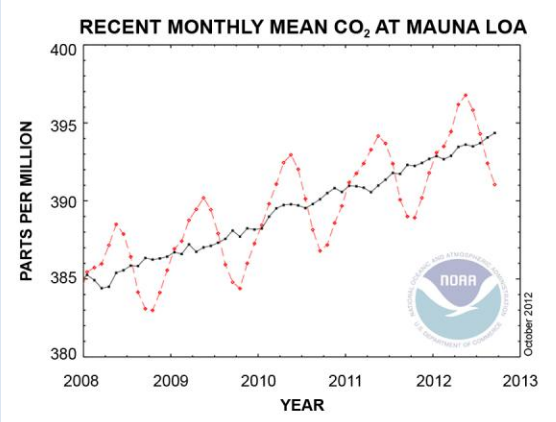
- Global average land surface temperature has increased by about 0.9°C since the 1950s. During the same period, the prevalence of extreme warm anomalies has increased and the prevalence of extreme cool anomalies has decreased.
- There is no obvious long-term trend in global annual precipitation over land. However, there is strong evidence that precipitation has occurred in more extreme events for most of the northern hemisphere.
- Higher temperatures combined with more extreme precipitation have combined to produce increasing prevalence of severe freshwater deficits since about 1980 and a much smaller increase in the prevalence of freshwater surpluses since about 1990.
- Most of the permafrost observatories in the Northern Hemisphere show significant warming of permafrost since about 1980-1990.
- The minimum September arctic ice extent for each of the past five years (2007-2011) was lower than at any other year in the period of record and declining at an average rate of about 12% per decade.

The climate of the past decade has been unusual. Global average surface temperature in each of the ten years from 2002 through 2011 ranked among the top 13 years in a 132-year instrumental record that begins in 1880 (NCDC, 2012). This decade has also been marked by a number of high impact weather related disasters that include dramatic heat waves, droughts, floods, and storms (WMO, 2011; NOAA, 2012; NOAA, 2011). These phenomena are occurring at a time marked by apparent changes in the basic climate system. Human-induced climate changes are evidenced by numerous scientific measurements (see box below). Naturally induced climate changes are evidenced by active El Niño-Southern Oscillations, the Atlantic Multidecadal Oscillation, and other regional oscillations. We examine the documented empirical record and describe the evidence that makes it clear that the intensity of recent unusual events exceeds normal expectations and that their extent is worldwide, affecting people where they live, where they draw upon fresh water resources, and where they grow food.

This section begins with a review of the observational record for surface temperatures, precipitation, floods, and droughts, with a particular focus on trends in the prevalence of extremes. It then reviews trends in the observed impact of climate changes on arctic ice, permafrost, glaciers, ice caps, ice sheets, and sea level. This survey will provide a basis for understanding the scale and scope of extreme events and manifestations of changes in important physical components of the Earth system that can affect weather patterns. With observational evidence, we illustrate actual changes in extreme weather patterns anticipated in Section 3, "Our Current Understanding of the Climate System", and set the stage for Section 5, "Prospects for the Near-Term Future."

GROWING EVIDENCE OF HUMAN-INDUCED CLIMATE CHANGE

Observations of key indicators related to climate change over the past five years are demonstrating clearly that the factors associated with Earth's radiative energy imbalance are changing in a way that is consistent with the basic physics of anthropogenic climate change driven by increased emission of greenhouse gases offset to some extent by emissions of industrial aerosols.



Multiple lines of observational evidence conclude that atmospheric concentrations of greenhouse gases are increasing and that most of this increase can be attributed to the combustion of fossil fuels (Blunden et al, 2011). Carbon dioxide (CO_2) concentrations have increased from approximately 340 ppm in 1980 to approximately 397 ppm today (NOAA Mauna Loa Observatory, 2012). One can infer that most of this increase is due to fossil fuel combustion because:

1. The north-south difference in concentrations is increasing in a manner that is consistent with CO_2 emissions from fossil fuel combustion, predominantly in the Northern Hemisphere, and
2. Measurements of tracers indicate fossil fuel combustion. Decreasing ^{14}C in CO_2 is a result of adding CO_2 from fossil fuel combustion (depleted of ^{14}C); ^{13}C in CO_2 shows that the added CO_2 is of organic origin; and a decrease in the ratio of O_2:N_2 is consistent with O_2 consumption by fossil fuel combustion (Blunden et al., 2011).

The current rate of increase in atmospheric CO_2 is exceptional when compared to changes on geological time scales, as assessed from measurements of air trapped in ice-cores (Blunden et al, 2011). Atmospheric concentrations of other major greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) are also increasing. "After a decade of near-zero growth, atmospheric methane increased globally in 2007 and 2008 by ~7.5 ppb per year" and by ~5 ± 2 ppb in 2009 and 2010 (Blunden et al, 2011). N_2O concentrations are increasing, due in part to application of fertilizers on agricultural crops, at a rate of 0.75 ± 0.01 ppb per year (Blunden et al, 2011).

Other key evidence is routinely monitored by NOAA and others:

- Global average surface temperature is rising
- Global average sea surface temperature is rising
- Sea level is rising
- Global upper ocean heat content is rising
- Specific humidity is increasing
- Northern hemisphere snow cover is decreasing
- The lower stratosphere is cooling while the upper troposphere is warming
- Energy from the sun has not significantly increased.

The last two observations support the view that increased atmospheric concentrations of greenhouse gases are largely responsible for observed increases in global average surface temperature, increases of temperatures in the upper troposphere, and decreases of temperatures in the stratosphere (where infrared radiation emitted by CO2 can communicate directly to space). The latter two conditions may be considered as critical fingerprints of GHG-induced change.

4.1 Surface Temperature

Multiple independent estimates of trends in global mean temperature over time have all reached the same conclusion. Global average surface temperature (corrected for heat island effects) and global average surface temperature over land only have both increased significantly since the 1950s. The results from a recent re-analysis of global land surface temperature records are depicted in Figure 15 below (Rohde et al., 2012). This analysis reports that "the global land mean temperature increased by 0.89 ± 0.06 C in the difference of the Jan 2000-Dec 2009 average from the Jan 1950-Dec 1959 average (95% confidence for statistical and spatial uncertainties)." A parallel analysis concluded that "urban warming does not unduly bias estimates of recent global temperature change" (Wickham et al., 2012). As discussed in Section 3, some have observed that the rate of change appears to have leveled off or even reversed in the past decade (Allegre et al., 2012). In a climate with strong inter-decadal variability, such periods are to be expected, even when the long-term trend is dominated by warming (Easterling and Wehner, 2009; Rohde et al., 2011; Rohde et al. 2012). During these "hiatus" periods, it is possible that the excess atmospheric energy is absorbed by deep ocean waters (Meehl et al., 2011) and/or that the negative direct and indirect forcing effects of short-lived atmospheric aerosols have increased, particularly in Asia, since the mid-1990s (Murphy et al., 2009; Wild, 2009; Kaufman et al., 2011; Wild, 2012).

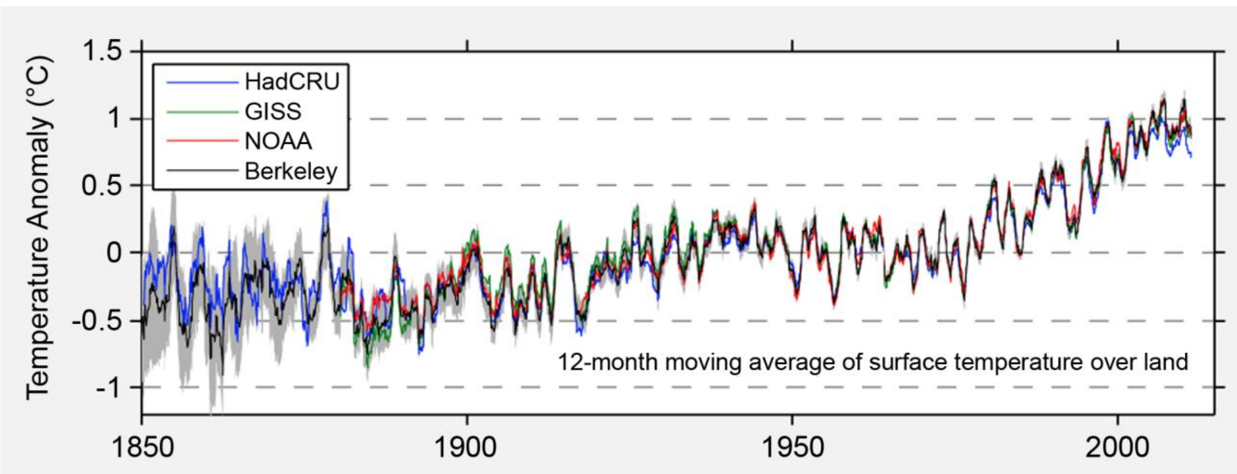


Figure 15. 12-month Moving Averages for Four Independent Estimates of Global Mean Land Surface Temperature, and a Gray Band Corresponding to the 95% Uncertainty Range on the Berkeley Average.

Source: Rohde et al., 2012.

While it is clear that global average temperatures are increasing, the most imminent consequences to national security occur during periods of temperature extremes. When people and ecosystems are confronted with temperatures well outside their range of expectations based on recent prior history, they often respond in atypical ways that can pose national security challenges. These effects are magnified by today's globalized political-economy when episodes of extreme temperatures occur at many different places at once – a phenomenon that Thomas Friedman has popularized as "global weirding" (2010).

Figure 17 and Figure 18 present the key results from an analysis of trends in the prevalence of temperature extremes. This analysis examines the estimated "return periods" of annual average temperatures for land surface grid cells covering approximately 64,000 sq km each, based on a climatology constructed from observed annual average temperatures for 1910-2010 obtained from the NASA Goddard Institute for Space Studies (GISS, Hansen et al., 2010). The 250 km version of the GISS dataset is used here. Only grid cells with at least 10 months of good data in 80% of the years being analyzed are used. Data for missing cell-months are replaced with mean values for that month over the period of analysis. This criterion is used to avoid potential bias associated with sparse weather stations in the high-latitude regions of the world where warming is most pronounced. Annual average temperatures for qualifying cells are fitted using the generalized extreme value (GEV) distribution (Hosking et al., 1985; Hosking, 2009). The inverse of the return period is the probability of observing an anomaly of a given magnitude or worse in a given year. For example, a return period of +30 means than one would expect to observe an "above median" (or "hot") anomaly of a given magnitude or worse in 1 out of 30 years. Similarly, a return period of -10 means one would expect to observe a "below median" (or "cold") anomaly of a given magnitude or worse in 1 out of 10 years. Figure 16 depicts the cells used to generate the distributions, and the cells used to compute occurrence of extreme annual average temperatures.

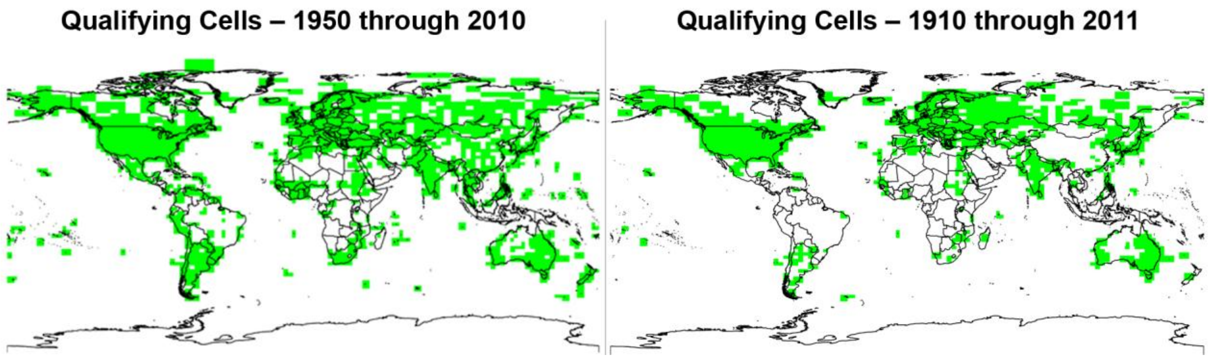


Figure 16. Cells from GISS Temperature Dataset Used to Generate Return Periods.

The left map shows the cells that qualify when analyzing the period from 1950 through 2011, and the right map shows the cells that qualify when analyzing the period from 1910 through 2011.

The resulting trends in the prevalence of extreme annual average temperatures over the measured land surface are shown in Figure 17. The red bars in these charts depict the fraction of the measured land area with above median annual average temperature anomalies (warm events) that exceed a 30 year return period threshold, and the blue bars depict the fraction of the measured land area with below median anomalies (cool events) that exceed a 30 year return period threshold. For reference, the gray area depicts the value one would expect with a stationary and spatiotemporally random climate. Figure 17 (left) shows the trend using a base period of 1910-1970 to estimate return frequencies. This plot shows a relatively stable temperature regime throughout the base period (except for widespread cold events in 1917), and periods with above and below expected prevalence of warm and cold years in each decade through the 1970s. Beginning in the early 1980s, the prevalence of warm years vastly exceeds anything observed in the base period, and the prevalence of cold events virtually disappears by the 2000s. These changes are consistent as the base period is moved forward in time in Figure 17 (center and right), but successively less dramatic since the more recent baseline periods include more of the hot years.

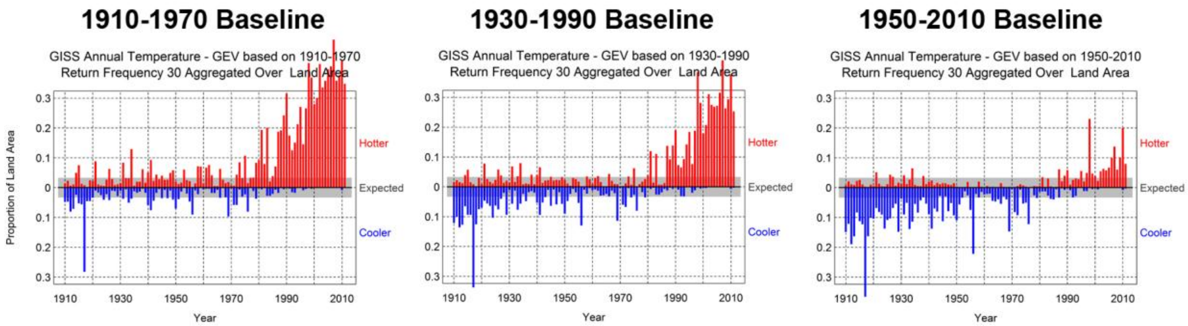


Figure 17. Trends in the Prevalence of Extreme Annual Average Temperatures (1910-2011) Using Three Baseline Periods (1910-1970, 1930-1990, and 1950-2010).

Red bars in these charts depict the fraction of the measured land area with above median annual average temperature anomalies (warm events) that exceed a 30-year return period threshold, and the blue bars depict the fraction of the measured land area with below median anomalies (cool events) that exceed a 30 year return period threshold.

Figure 18 presents a more detailed look at the prevalence of extreme temperatures using the 1950-2010 baseline period. Figure 18 (UL and UR) depict the trend in the proportion of the land surface experiencing 10- and 30-year annual average temperature anomalies using the 1950-2010 baseline. The red bars depict the area experiencing above median anomalies (hot temperatures), and the blue bars depict below median anomalies (cool temperatures). For reference, the gray area depicts the value one would expect with a stationary and spatiotemporally random climate. As above, these two plots show a clear trend towards significantly more prevalent hot annual average temperatures starting in the mid-1980s, coincident with a marked decline in the prevalence of cool average annual temperatures that begins in the mid-1970s. The prevalence of 30-year extremes appears to be partially correlated with ENSO variability. This correlation is less pronounced in the prevalence of 10-year extremes. To demonstrate that the trend toward more widespread high temperature anomalies is not limited to sparsely populated high latitude regions, Figure 18 (LL and LR) show the trends in the prevalence of 30-year temperature extremes using the 1950-2010 baseline period weighted by population circa 2000 (CIESIN, 2005) and by cereal production circa 2000 (Monfreda et al., 2008). These charts clearly show that the increasing prevalence of hot average temperatures, and the corresponding near disappearance of cold average temperatures, is occurring in the populated and agriculturally productive regions of the world, not just in the sparsely populated high-latitudes where the absolute change in temperature has been highest.

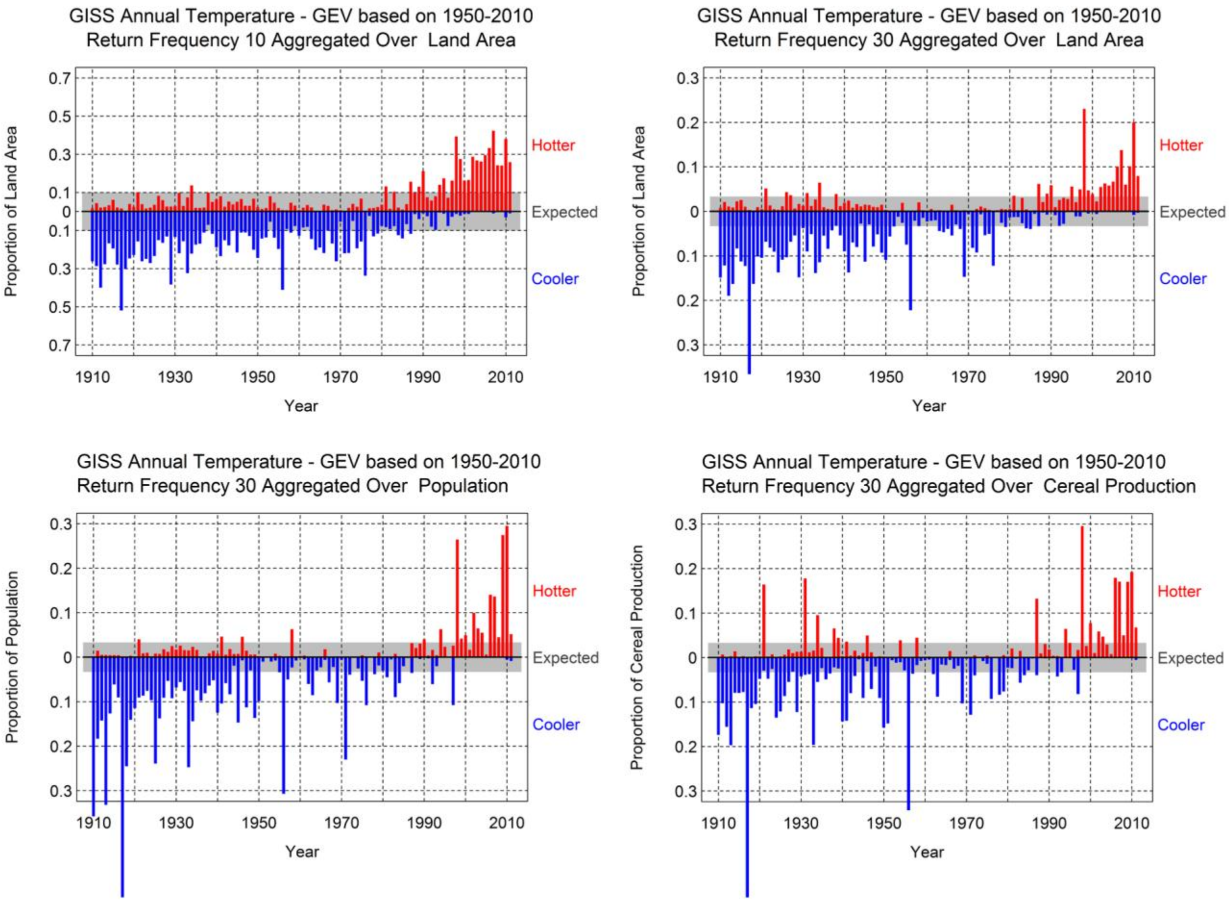


Figure 18. Trends in the Prevalence of Extreme Annual Average Temperature Using 1950-2010 Baseline.

(UL) Fraction of land area experiencing temperature extremes with an estimated return frequency of 10 years or greater. (UR) Fraction of land area experiencing temperature extremes with an estimated return frequency of 30 years or greater. (LL) Fraction of population (ca. 2000) living in areas with an estimated return frequency of 30 years or greater. (LR) Fraction of global cereal production (ca. 2000) in areas with an estimated return frequency of 30 years or greater.

The results depicted in Figure 18 are consistent with similar analyses performed by Hansen et al. (2012a, 2012b), Meehl et al., (2009), Trewin and Vermont (2010), Brown et al. (2008), and Alexander et al. (2006) using alternate temperature datasets and statistical methods. The Hansen et al. results are most comparable because they directly examine extremes in annual and seasonal average temperature using the GISS temperature dataset. They report increasing prevalence of extreme temperatures in both winter and summer periods. Figure 19 depicts how the distribution of summer time temperature anomalies over Northern Hemisphere land has shifted towards hotter temperatures and broadened by decade. The Brown et al. and Alexander et al. analyses describe consistent trends in extremes of daily minimum and maximum temperatures. Meehl et al. examine the ratio of record high maximum temperature to record low minimum temperatures in the U.S. and find that the ratio has been steadily increasing since 1970. Trewin and Vermont examine ratios of record highs to lows in Australia and find that the ratio has been increasing since the 1960s.

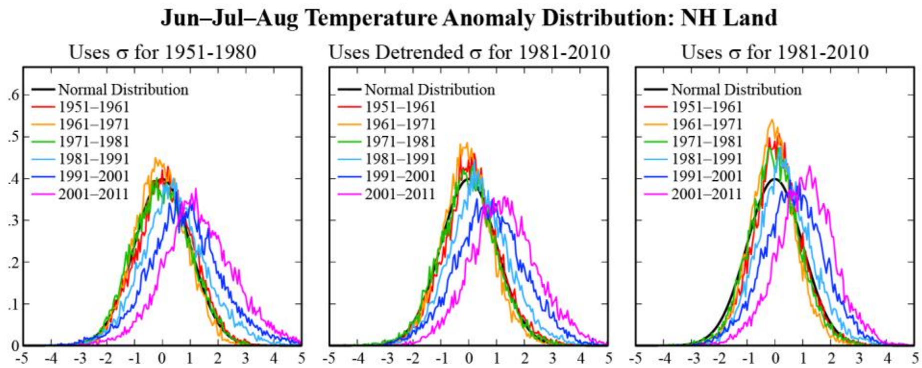


Figure 19. Distributions of Northern Hemisphere Summer Temperature Anomalies over Land by Decade (Source: Hansen et al, 2012a).

Using the GISS temperature dataset, Hansen et al. depict how the distribution of summer time temperature anomalies over Northern Hemisphere land has shifted towards hotter temperatures and broadened by decade - shifting the tail of the distribution toward more extreme temperatures in summer and in winter periods.

The global trend in average land surface temperature is clearly related to the increase in the prevalence of extreme annual average temperatures as illustrated in Figure 20. These graphs overlay the trend in mean global surface temperature over land derived from the GISS data on the trends in prevalence of 10- and 30-year extremes from Figure 18 (a) and (b) above. A single scale factor is applied to the global surface temperature means to fit them to the range of the prevalence. The proportion of land area with extreme average annual temperatures is clearly related to the global average temperature anomaly over land. Global mean temperature over land anomalies explain about 90% of the difference in the proportion of measured land area experiencing hot-cold extremes using a 10-year threshold (left plot) and 73% of the difference using a 30-year threshold (right plot). This suggests that any future increases in global mean temperature over land will likely be accompanied by greater prevalence of extreme temperatures. The prevalence in 30-year extremes appears to be partially correlated with ENSO variability in addition to global mean temperature over land. This implies that the prevalence of the most extreme local annual mean temperatures during the next decade will rise along with global mean temperature, and is likely to be greatest during periods of ENSO variability.

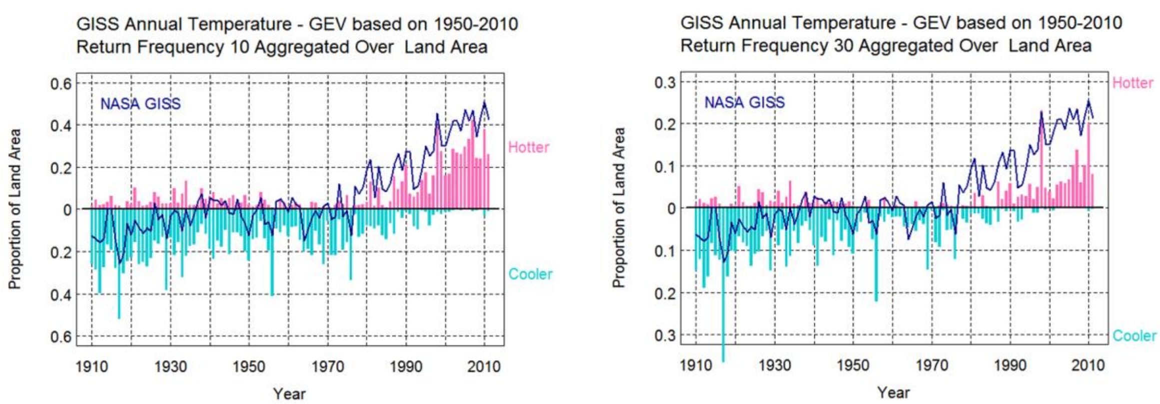


Figure 20. Comparison of Global Mean Land Surface Temperature Prevalence of 10- (left) and 30-year (right) Extremes.

Global mean land surface temperature data are scaled to fit the range in prevalence.

Figure 21 depicts in map form the maximum return frequency per cell per decade from 1910 to 2010, using a base period of 1950-2010. The increased occurrence of 10- to 30-year high average annual temperatures (yellows, oranges, reds) starting in 1981-1990 is unmistakable. Aside from the high return frequencies observed in the U.S. in the 1920's and 1930's, only small pockets of high return frequencies are visible from 1910 through 1980. Clearly the proportional occurrence of unusually high average annual temperatures has increased in the last few decades. Also apparent in the figure is the fact that these high average temperatures are distributed over most of the land area for which there are qualified cells.

Figure 22 summarizes results of a similar analysis restricted to Mexico and the U.S./Mexico border region (Texas, New Mexico, Arizona, and Southern California) using the 1950-2010 baseline period. While some of the results for this region mirror those for the global analysis, there are some important differences. While there is a clear trend toward greater prevalence of extreme high average annual temperatures beginning in the mid-1990s as in the global analysis, it is not unique. There are several years in the period 1920-1934 that also exhibit widespread occurrence of extreme high average annual temperatures. Low average annual temperatures in the U.S./Mexico border region occur primarily in the 1910-1920 and 1970-1990 periods. Those periods show up in the global prevalence results, but are less widespread. These results suggest that temperature extremes in this region are dominated by multi-decadal oscillations, but that the extremes in the current period are somewhat more prevalent and more closely sequenced in time than in the 1920s and 1930s. This analysis cannot discern whether this is simply natural variability, a general warming trend, effects of rapid regional industrialization that resulted in large emissions of aerosols from coal-fired power plants and the subsequent reduction in these emissions due to the Clean Air Act of 1990 as suggested by Leibensperger et al. (2012), or interactions among all three of these influences.

In general, the analysis of trends in the prevalence of extreme annual average temperatures for specific regions is less conclusive than the global analysis. This is not surprising, given that the climate in these regions is dominated by natural variability. However, this makes the results from the global analysis even more compelling. When aggregating across many regions, each controlled in different ways by natural variability, there is a clear trend toward greater prevalence of extremes that coincides with global average annual land surface temperature anomalies.

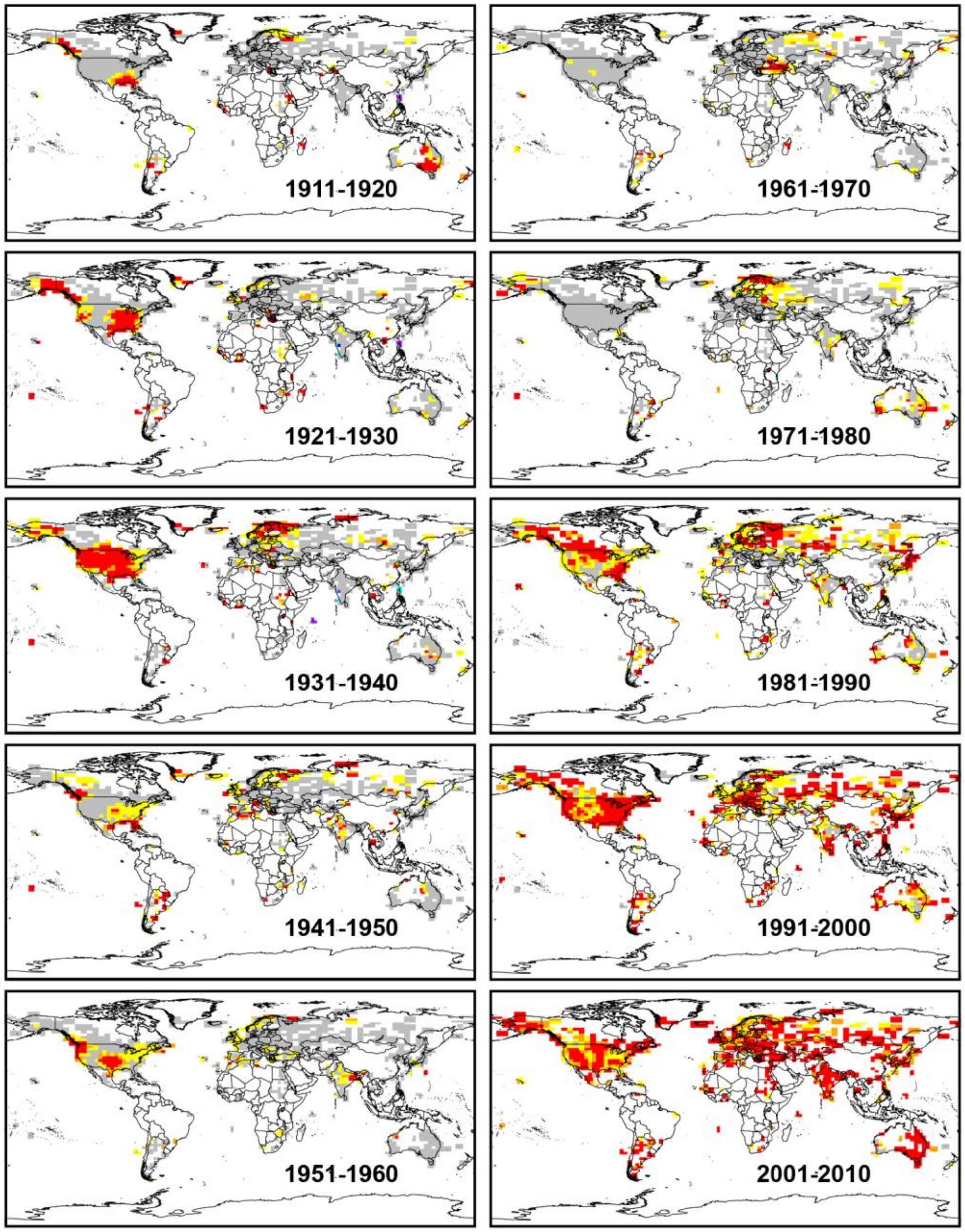


Figure 21. Maximum Return Period of Above Median Annual Average Temperature Anomalies by Decade (1910-2010) Using a 1950-2010 Base Period.

Gray= <10, yellow= 10-20, orange= 20-30, red= ≥30, white= insufficient data. An increase in the global and regional occurrence of 20- and 30-year above median land surface temperature anomalies is evident from 1910 through 2010. This figure depicts the return period of the largest above median temperature anomaly occurring over each ten-year period since 1910 in each grid cell with near continuous measurements throughout the period. With the notable exception of the U.S. dust bowl era, few locations experienced 20- or 30-year above median temperature anomalies in the period 1910 to 1980 (orange and red in the figure). However, the majority of the measured land surface experienced 30-year high temperatures at least once in the period 2001-2010 (red in the figure). This analysis has shown that the high-temperature anomalies are occurring not only in unpopulated areas such as the boreal and Arctic regions where average temperatures have increased the most, but also in agricultural croplands and populated areas.

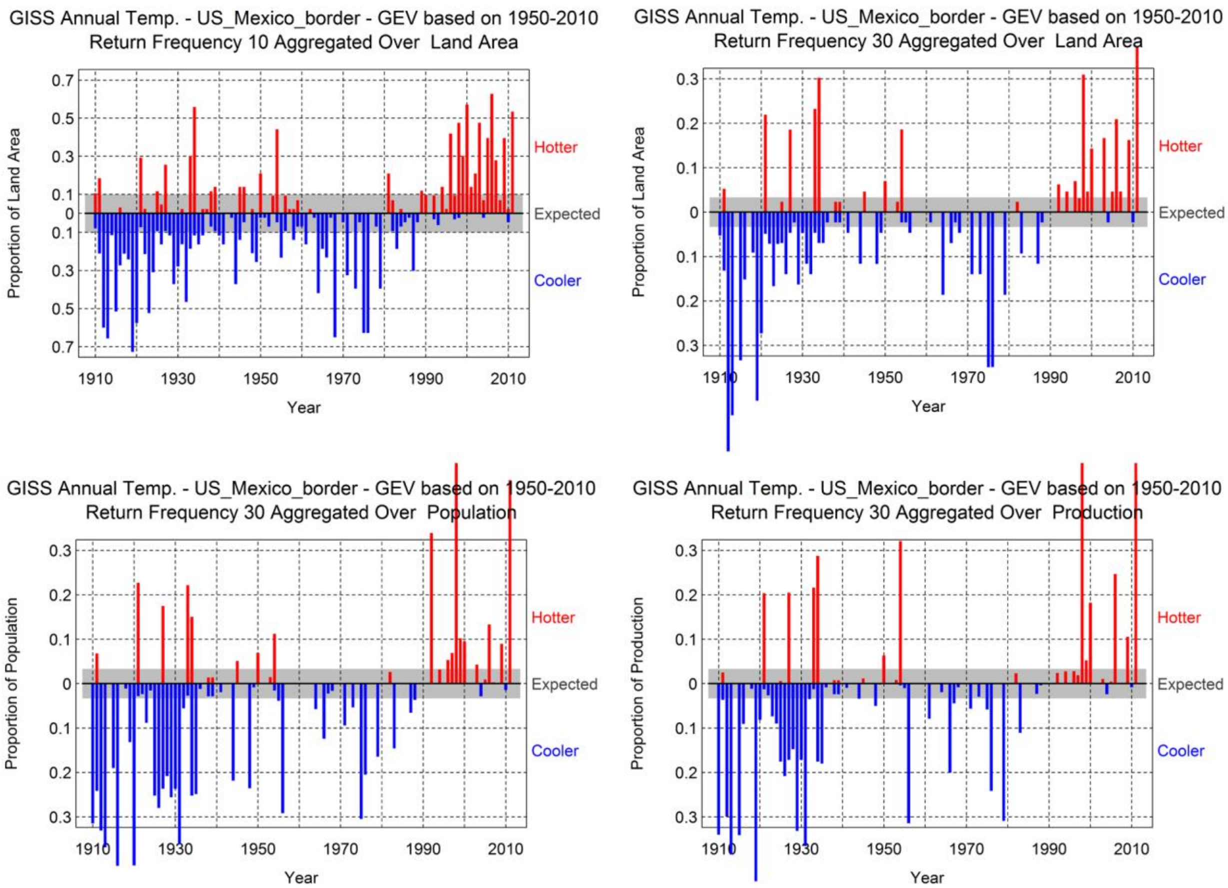
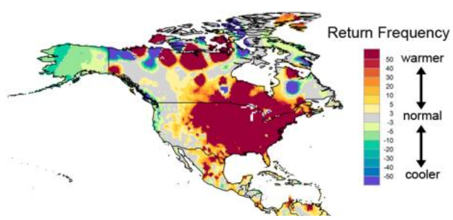


Figure 22. Trends in the Prevalence of Extreme Annual Average Temperature in Mexico and the U.S./Mexico Border Region.

(UL) Fraction of regional land area experiencing temperature extremes with an estimated return period of 10 years or greater. (UR) Fraction of regional land area experiencing temperature extremes with an estimated return period of 30 years or greater. (LL) Fraction of regional population (ca. 2000) living in areas with an estimated return period of 30 years or greater. (LR) Fraction of regional cereal production (ca. 2000) in areas with an estimated return period of 30 years or greater.

NORTH AMERICAN "YEAR WITHOUT A WINTER"

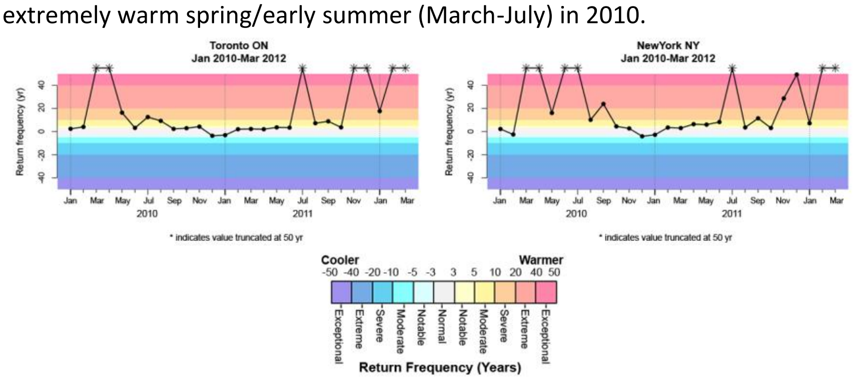
The past decade has been marked by a number of high impact weather related disasters that include dramatic heat waves, droughts, floods, and storms (WMO 2011; NOAA 2012; NOAA 2011). In one particular event during March 2012, a large portion of North America experienced a prolonged period of exceptionally warm temperatures that broke numerous temperature records throughout the region by large amounts, leading astute observes to proclaim "summer in March" (Masters 2012). The month as a whole was the "warmest March on record for the contiguous United States, a record that dates back to 1895. The average temperature of 51.1°F was 8.6°F above the 20th century average for March and 0.5°F warmer than the previous warmest March, in 1910. Of the more than 1,400 months that have passed since the U.S. data record began, only one month, January 2006, has seen a larger departure from its average temperature than March 2012" (NOAA 2012). In the period from January 1 through June 10, 2012, the ratio of record daily highs to record daily lows in the conterminous United States exceeded 10:1 (Walton, 2012).



Monthly average temperature anomaly expressed as return frequency for March 2012. Dark red areas have above median temperature (relative to 1950-2010) with an estimated return period of greater than 50 years.

The U.S. map illustrates that the eastern two-thirds of the United States and much of Canada experienced temperature anomalies with expected return periods of more than 50 years. While the March record temperatures made headlines, it has not been as widely reported that the entire winter was unusually warm and followed an extremely warm spring and summer in 2010. The charts show the monthly temperature anomalies expressed as return period for Toronto and New York City from January 2010 through March 2012. During the winter of 2011-12 (November through March) the return period of Toronto's monthly average temperature anomaly exceeded 50 years in 4 of the 5 months, and the remaining month (January) had a return period of almost 20 years. In New York City, both February and March exceeded the 50 year threshold, December was just shy of the 50 year threshold, November had a 30 year return frequency, and December was above normal. During the warm spring/early summer in 2010, 4 out of 5 months from March through July exceeded the 50 year return period threshold in New York City, and March and April exceeded the 50 year threshold in Toronto.

Monthly average temperature anomalies expressed as return frequency for Toronto and New York City (Jan 2010 - March 2012). The winter of 2011/12 (November – March) was extremely warm in both cities. This followed an extremely warm spring/early summer (March-July) in 2010.



While one extreme event does not constitute a trend, the analysis presented in Chapter 3 indicates the prevalence of extreme temperatures has been increasing in parallel with global average temperatures.

4.2 Precipitation

The trends in global annual precipitation anomalies over land derived from three datasets are shown in Figure 23. No clear long-term pattern emerges from these data. Although observational evidence to date does not suggest a robust long-term trend in global annual precipitation over land since 1900 (IPCC AR4, Working Group 1 (WG1), §3.3.2), shorter-term analyses that focus on the period from 1990 to present, and benefit from the availability of satellite sensors with consistent coverage over the entire globe, do find evidence of an accelerating hydrological cycle that is consistent with Figure 23. However, there is increasingly strong observational evidence that annual maximum 1-day and 5-day precipitation (RX1D and RX5D) and the contribution of large precipitation events to annual totals are rising with time for the vast majority of the Northern Hemisphere (Seung-Ki et al., 2011; Alexander et al., 2006; and Gleason et al., 2008). As explained in Section 2, this evidence is consistent with the Clausius–Clapeyron relation that establishes that the warmer air has increased capacity to hold water vapor. It is also consistent with observational records that indicate an increasing trend in specific humidity over land and oceans since the early 1970s, with "apparent peaks during strong El Niño events" and some flattening from 1998 through 2009 (Blunden et al., 2011). Total column water vapor has increased at 0.30 +/- 0.08 mm/decade since 1987 and also shows large peaks during strong El Niño events and troughs during strong La Niña events (Blunden et al., 2011). With greater capacity to hold water vapor, one expects to observe an increased number of large precipitation events.

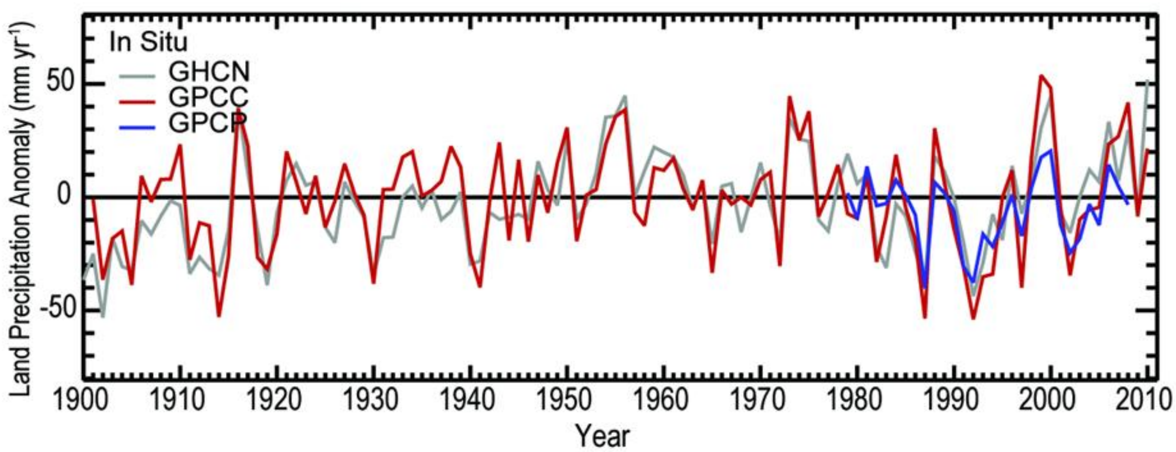


Figure 23. Global Average Precipitation Annual Anomalies over Land from in situ Data Relative to a 1961-1990 Base Period.

Image source: Blunden, J., D. S. Arndt, and M. O. Baringer, 2011.

Trend analysis of precipitation and related parameters was done using global land surface air temperature and precipitation data datasets specifically constructed for applications to global hydrology by the NOAA Climate Prediction Center (Fan and van den Dool, 2008 for temperature; Chen et al., 2002 for precipitation). These datasets provide monthly average temperature and total monthly rainfall for each 0.5 x 0.5 degree land surface area for the period 1950-present. Analysis of average annual temperature based on this data set was found to be comparable to that reported above using the GISS temperature record. Figure 24 presents the key results from an analysis of trends in the prevalence of annual precipitation extremes. This analysis examines the estimated return periods of total annual precipitation for each 0.5 x 0.5 degree land surface grid cell based on a climatology constructed from observed annual total precipitation for 1950-2010 (Chen et al., 2002) and fitted using the generalized extreme value distribution.

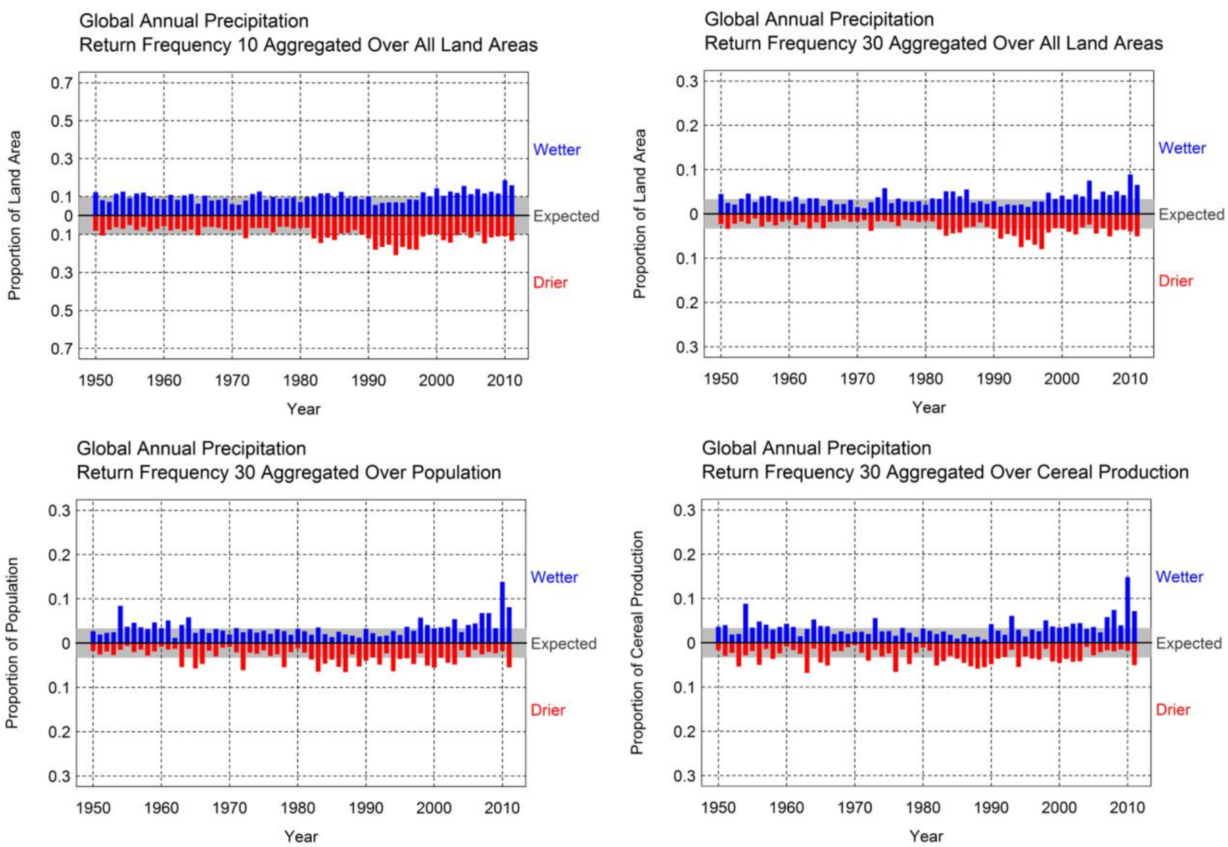


Figure 24. Trends in the Prevalence of Extreme Total Annual Precipitation.

(UL) Fraction of land area experiencing precipitation extremes with an estimated return period of 10 years or greater. (UR) Fraction of land area experiencing precipitation extremes with an estimated return period of 30 years or greater. (LL) Fraction of population (ca. 2000) living in areas with an estimated return period of 30 years or greater. (LR) Fraction of global cereal production (ca. 2000) in areas with an estimated return period of 30 years or greater.

As with the temperature analysis above, the inverse of the return period is the probability of observing an anomaly of a given magnitude or worse in a given year. Figure 24 (UL and UR) depicts the trend in the proportion of the land surface experiencing 10 and 30 year total annual precipitation anomalies. The red bars depict the area experiencing below median anomalies (low annual precipitation), and the blue bars depict above median anomalies (high annual precipitation). For reference, the gray area depicts the value one would expect with a stationary and spatiotemporally random climate. As with the global annual precipitation anomalies, no strong trend emerges over the global land surface. However, 2004, 2010, and 2011 do show increased prevalence of 30-year high annual precipitation and in the 1990s an increased prevalence of low annual precipitation. These results may be biased by the lack of weather stations in the high latitudes. In order to address these potential biases we weighted the results for 30-year anomalies by population circa 2000 (CIESIN, 2005) and by cereal production circa 2000 (Monfreda et al., 2008) as shown in panels (LL and LR). While not as strong as for temperature and too short a period to constitute a trend, these charts show that the prevalence of high annual precipitation in the populated and agriculturally productive regions of the world is elevated in 1998, 2004, 2007-2008, and 2010-2011. This confirms that the recent period has had more prevalent annual precipitation extremes relative to the historical record. It is not clear whether this is due to natural variability or radiative forcing.

The lack of clear trends in the global prevalence of extreme annual precipitation in this analysis is not surprising. However, one would expect to find regional trends, particularly in areas dominated by the South Asian monsoon which many expect to exhibit increased precipitation intensity as the result of anthropogenic climate change despite weakening of the circulation (IPCC AR4, WG1, §11.4). Figure 25 shows the results of an analysis of annual precipitation extremes restricted to the Indus, Ganges, and Brahmaputra River basins. These results clearly show an increase in the prevalence of precipitation extremes over the past six years (2005-2011). The prevalence of extremes during this period is greater than an earlier period of prevalent extremes in the 1950s. As with the analysis of temperature extremes in Mexico and the U.S./Mexico border region, this analysis cannot discern whether the recent increase in the prevalence of annual precipitation is driven by natural variability, a general trend toward increased precipitation, changes in aerosols, or interactions of all three phenomena. However, the results are consistent with theory regarding anthropogenic influences on the South Asian monsoon that expect "monsoonal circulations to result in increased precipitation due to enhanced moisture convergence, despite a tendency toward weakening of the monsoonal flows themselves" (IPCC FAR WG1, pp. 849) and a "large increase of intense precipitation events during the Indian summer monsoon over [the] Arabian Sea, tropical Indian Ocean, [and] South Asia" (IPCC FAR WG1, pp. 863).

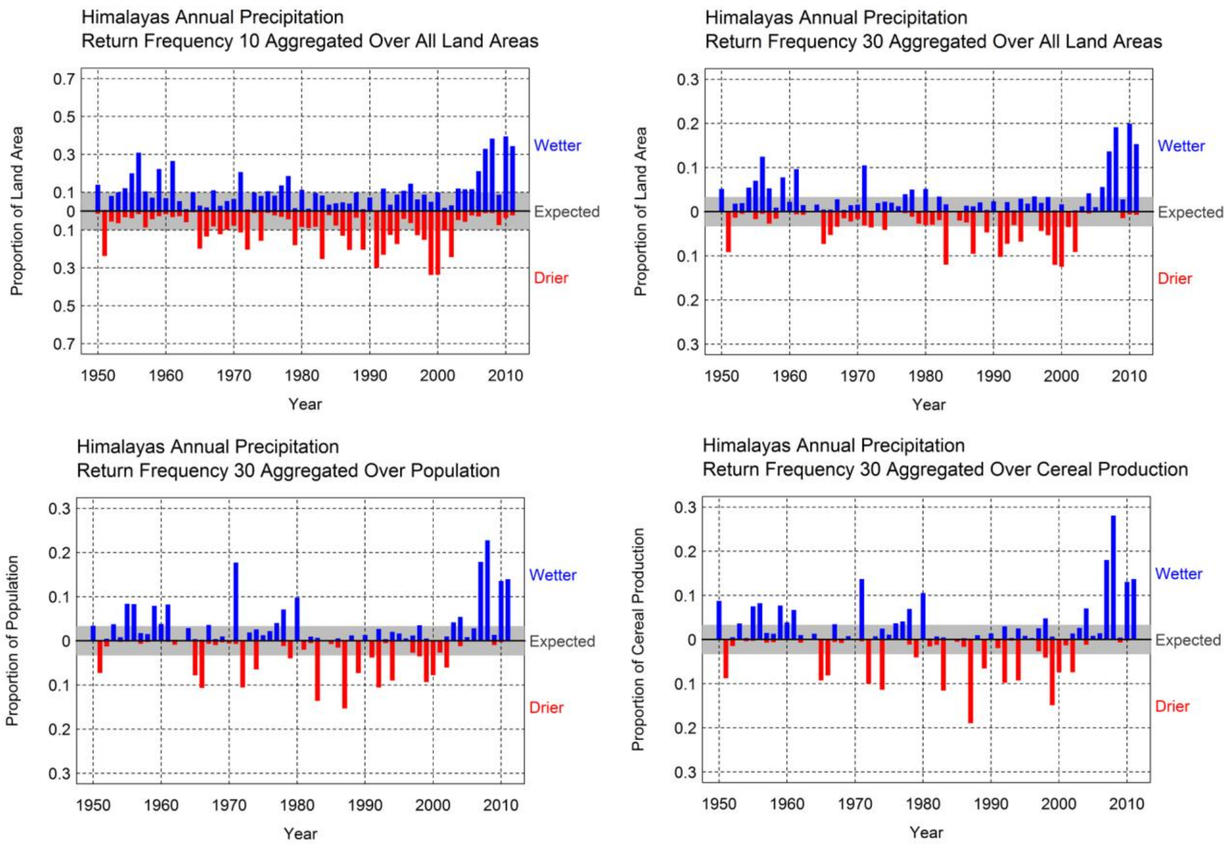


Figure 25. Trends in the Prevalence of Extreme Total Annual Precipitation in the Indus, Ganges, and Brahmaputra River Basins.

(UL) Fraction of regional land area experiencing precipitation extremes with an estimated return period of 10 years or greater. (UR) Fraction of regional land area experiencing precipitation extremes with an estimated return period of 30 years or greater. (LL) Fraction of regional population (ca. 2000) living in areas with an estimated return period of 30 years or greater. (LR) Fraction of regional cereal production (ca. 2000) in areas with an estimated return period of 30 years or greater.

4.3 Floods and Droughts

Given greater prevalence of temperature extremes and greater proportions of annual precipitation from heavy precipitation events, one would expect greater frequencies of drought and flood. That said, the IPCC Special Report on managing the Risks of Extreme Events (IPCC SREX) was only able to conclude that “there is medium confidence that since the 1950s some regions of the world have experienced trends toward more intense and longer droughts, in particular in southern Europe and West Africa, but in some regions droughts have become less frequent, less intense, or shorter, for example, central North America and northwestern Australia” (pp. 174) and that “there is limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at a regional scale because the available instrumental records of floods at gauge stations are limited in space and time, and because of confounding effects of changes in land use and engineering.”

Figure 26 presents the key results from an analysis of trends in the prevalence of annual composite freshwater surpluses and deficits conducted by the IC. This analysis uses the precipitation dataset described above, together with a compatible gridded temperature dataset (Fan and van den Dool, 2008) to drive a reduced form land surface model that operates with monthly time steps and 0.5 degree resolution. The composite deficit index is computed as the maximum of the return period for soil moisture deficits, total blue water (uninhibited flow accumulated runoff) deficits, and evapotranspiration deficits (potential minus actual evapotranspiration). This index represents the "worst" of three types of droughts (meteorological, hydrological, and agricultural). Conversely, the composite surplus index is computed as the maximum of the return frequencies for runoff and total blue water (uninhibited flow accumulated runoff). Note that we have explicitly changed our language from "drought" and "flood" to "deficit" and "surplus" to avoid some of the definitional issues noted in the IPCC SREX.

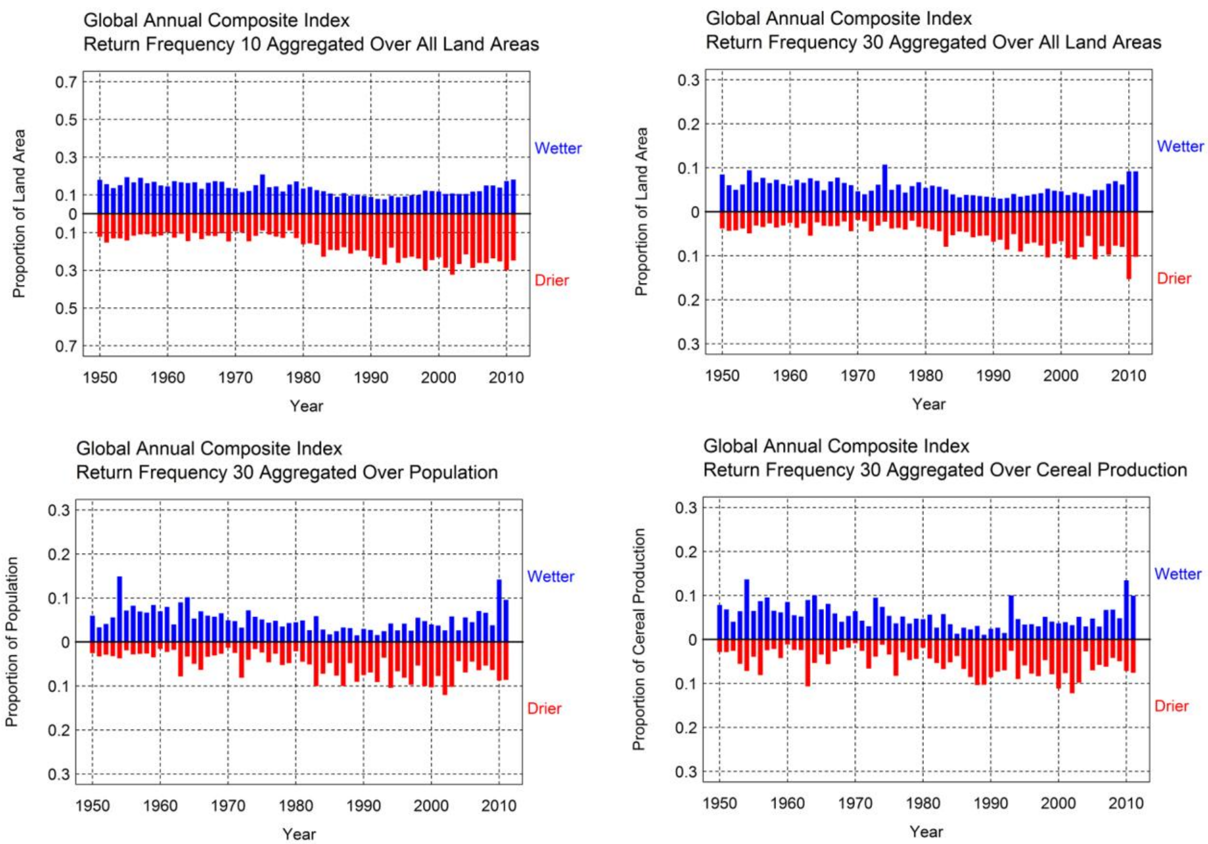


Figure 26. Trends in the Prevalence of Extreme Composite Freshwater Surplus and Deficit Indices.

(UL) Fraction of land area experiencing composite freshwater surplus and deficit extremes with an estimated return frequency of 10 years or greater. (UR) Fraction of land area experiencing freshwater surplus and deficit extremes with an estimated return frequency of 30 years or greater. (LL) Fraction of population (ca. 2000) living in areas with an estimated return frequency of 30 years or greater. (LR) Fraction of global cereal production (ca. 2000) in areas with an estimated return frequency of 30 years or greater.

Figure 26 (UL and UR) depict the trend in the proportion of the land surface experiencing 10- and 30-year composite surpluses and deficits. The red bars depict the areas experiencing deficits, and the blue bars depict surpluses. On a global basis the fraction of land area experiencing 10- and 30-year deficits steadily increases beginning in 1980. The trend for surpluses is less distinct. There is a steady increase from 1990-present, but this follows a period of decline from the mid-

1970s until 1990. The period from 1990 to present is, therefore, characterized by simultaneously increasing trends in both surpluses and deficits. As with the temperature and precipitation analyses above, these results are likely biased by the lack of weather stations at high latitudes. Performance of the reduced form land surface model is demonstrably worse in high latitudes. In order to minimize the effects of these potential biases we weighted the results for 30-year anomalies by population circa 2000 (CIESIN, 2005) and by cereal production circa 2000 (Monfreda et al., 2008) as shown in panels (LL and LR). These weighted results are similar to the land area results. There is a trend toward increased prevalence of deficits weighted by population and cereal production starting in 1980, and a rise in surplus freshwater weighted by population and cereal production from 1990 to present, with distinctly widespread surpluses in 2010 and 2011. As with land area, the recent rising trends in surpluses follow a decline in surpluses from the 1950s through 1990. The results for deficits are consistent with trends for soil moisture deficits from 1950-2000 by Sheffield and Wood (2008), who observe that “despite the overall [global] wetting trend, there is a switch in later years to a drying trend, globally and in many regions, which is concurrent with increasing temperatures. Although drought is driven primarily by variability in precipitation, temperature has an effect that appears to be exaggerated in the last decade or so especially in high northern latitudes.”

Earlier efforts to characterize the prevalence of freshwater surpluses and deficits made note of strong regional differences in trends. Figure 27 shows the results of an analysis of composite surplus and deficit indices for the “Eastern Mediterranean” (Egypt, Israel, Gaza Strip, West Bank, Lebanon, Jordan, Syria, Iraq, Kuwait, and Turkey). The results for this region are much more dramatic. The fraction of land area experiencing 10- and 30-year deficits has increased significantly beginning in the late 1980s. This increase occurred in three escalating cycles, each worse than the previous (1983-1990, 1998-2004, and 2007-2010). In general, the prevalence of 10- and 30-year surpluses has declined from peaks observed in the 1950s and 1960s. These patterns are amplified when weighted by where people live and grow food. The period from 2007-2010 that precedes the onset of the Arab Spring is dominated by extremely widespread freshwater deficits.

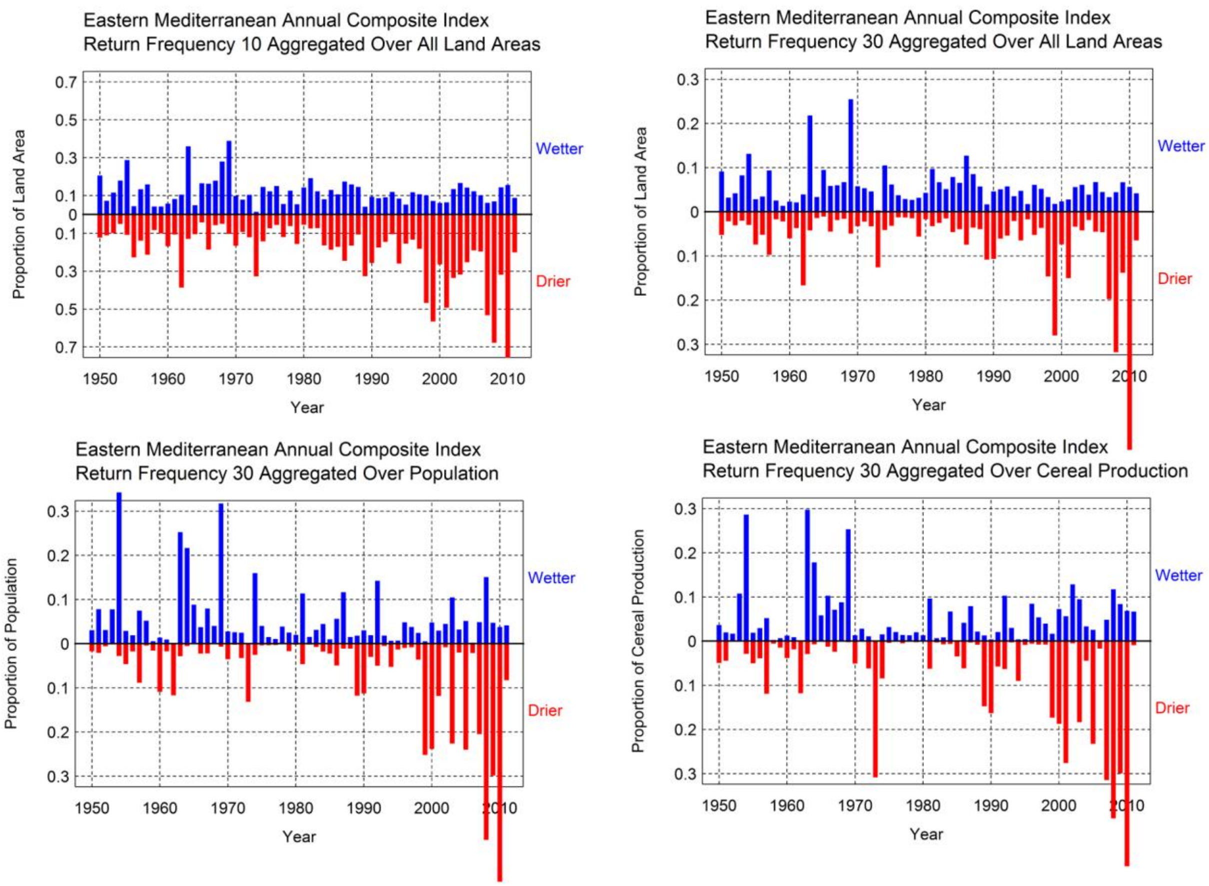


Figure 27. Trends in the Prevalence of Extreme Composite Freshwater Surplus and Deficit Indices for the Eastern Mediterranean.

(UL) Fraction of regional land area experiencing composite freshwater surplus and deficit extremes with an estimated return frequency of 10 years or greater. (UR) Fraction of regional land area experiencing freshwater surplus and deficit extremes with an estimated return frequency of 30 years or greater. (LL) Fraction of regional population (ca. 2000) living in areas with an estimated return frequency of 30 years or greater. (LR) Fraction of regional cereal production (ca. 2000) in areas with an estimated return frequency of 30 years or greater.

4.4 Permafrost

The economic and strategic importance of the Arctic is already high and is increasing due to the abundance of natural resources and its strategic location in terms of possible communication routes between the other parts of the world (Romanovsky, 2012). Military activity during the Cold War and recent economic development have increased construction activity related to infrastructure, oil and gas facilities, transportation networks, communication lines, industrial projects, and engineering maintenance systems. Climate change is likely to have significant impacts on existing arctic infrastructure and will influence the design of future development in the region.

The impact of climate warming on permafrost and the potential of climate feedbacks resulting from permafrost thawing have received a great deal of recent attention. Ground temperatures are a primary indicator of permafrost stability. The monitoring network of the Thermal State of Permafrost (TSP) program established during the Fourth International Polar Year has more than

600 sites across the Arctic (Figure 28). Most of the permafrost observatories in the Northern Hemisphere show substantial warming of permafrost since about 1980-1990. The magnitude of warming has varied with location, but was typically from 0.5 to 2°C. Permafrost is already thawing within the southern part of the permafrost domain. However, very recent observations documented propagation of this process northward into the continuous permafrost zone, especially in the Russian European North and in West Siberia. TSP measurements, combined with numerical modeling, now provide a relatively comprehensive assessment of panarctic permafrost dynamics during the last ~100 years. Projections of future changes in permafrost suggest that by the end of the 21st century, permafrost in the Northern Hemisphere may be actively thawing over a wide area.

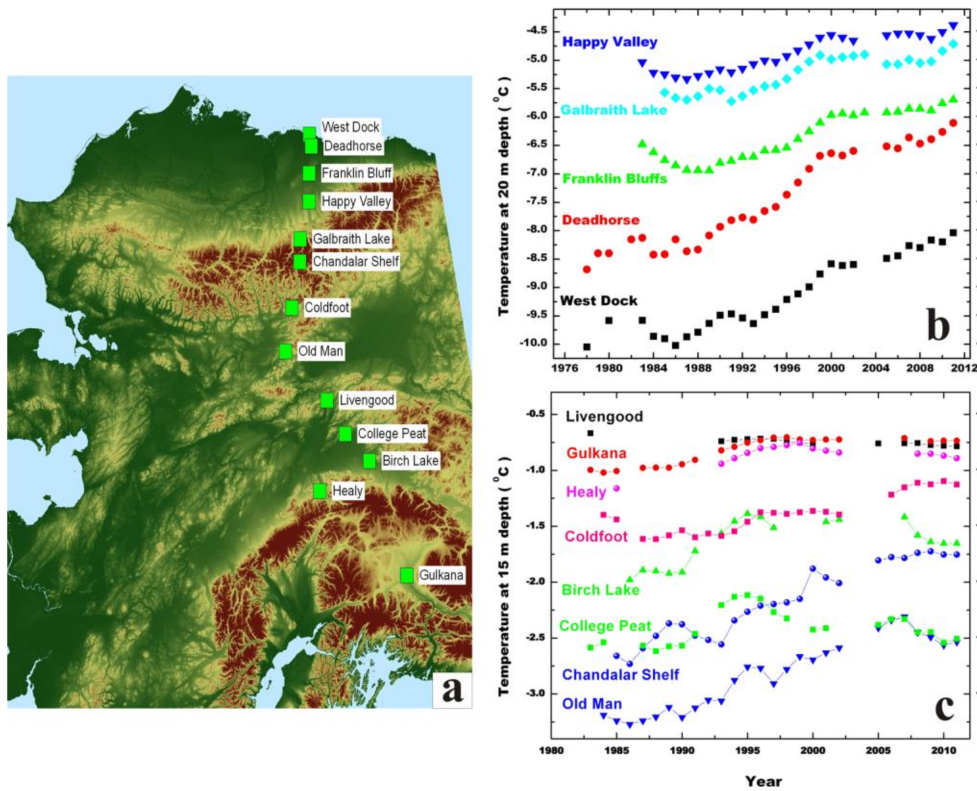


Figure 28. Changes in Permafrost Temperatures at Locations from North to South across the North Slope of Alaska in the Continuous Permafrost Zone, and in Interior Alaska.

Image source: Romanovsky VE, et al., 2011.

Various phenomena related to permafrost degradation are already commonly observed, including increased rates of coastal and river bank erosion, increased occurrences of retrogressive thaw slumps and active layer detachment slides, and drying of tundra lakes. Some northern communities are experiencing food insecurities due to the thawing of underground ice cellars used traditionally for food storage. Others have seen diminished quality and availability of fresh water, as lakes and streams used as water sources are affected by increased input of sediment and nutrients due to thawing of permafrost. The combination of thawing permafrost and erosion is also damaging community infrastructure such as buildings, roads, airports, pipelines, water and sanitation facilities, and communication systems. In some severe instances, permafrost thaw and related coastal erosion are forcing the relocation of entire communities.

The possible scale of direct ecological and economical damage from degrading permafrost has just started to be recognized, as are indirect threats from newly mobilized environmental contaminants. Climate feedbacks from degrading permafrost are expected due to the release of organic carbon and transfer of the key greenhouse gases carbon dioxide and methane to the atmosphere. Disturbances of high latitude permafrost regions, such as wildfires and thermokarst, are assumed to be accelerating both in frequency and intensity with adverse but poorly quantified effects on permafrost. Also of concern are the potential impacts from damaged oil and gas pipelines as a direct impact from the degrading and thawing permafrost in the Arctic regions. The rapid expansion of pipeline construction in Russian permafrost areas has caused problems with above and below ground pipelines due to thawing of ice-rich soils and frost heave of pipeline foundations.

To mitigate all possible impacts of permafrost degradation, an accurate and timely forecast of changes in permafrost based on a reliable permafrost observation system should be established. Permafrost research is becoming increasingly interdisciplinary, involving geophysicists, hydrologists, terrestrial and aquatic ecologists, geochemists, geologists, engineers, modelers, and sociologists. Despite our accumulating knowledge of changing permafrost, future permafrost dynamics and its impacts remain poorly quantified on the panarctic and especially local scales. To make progress, disciplines must team together to understand and to predict the patterns, processes, and consequences of permafrost thaw to the earth natural systems and to foresee their societal impacts.

4.5 Arctic Sea Ice

Perovich et al. (2011) have noted that there are two months that define the annual cycle for Arctic sea ice extent: September, when ice is at a minimum, and March, when it is at a maximum. Figure 29 illustrates the change in arctic sea ice extent during September and March relative to the means for 1979 to 2000. The minimum (September) extent for each of the past five years (2007-2011) is lower than for any other year in the period of record and has been declining at an average rate of 12% per decade. Most of this retreat has occurred “around the periphery of the Arctic Basin and in the Canadian Archipelago.” As a result, in September the southern route of the Northwest Passage has been open in each of the past five years, the northern route has been open for three of the past five years (2007, 2010, and 2011), and the Siberian Coast passage of the Northern Sea Route has been open for all but 2007. Similarly, but less dramatically, the maximum extent has been declining at an average rate of -2.7% per decade. In addition, there has been a dramatic decline of multi-year ice in recent years. Possible causes for this more rapid decline include a warming ocean, faster melting of thinner ice, and black carbon on the ice surface.

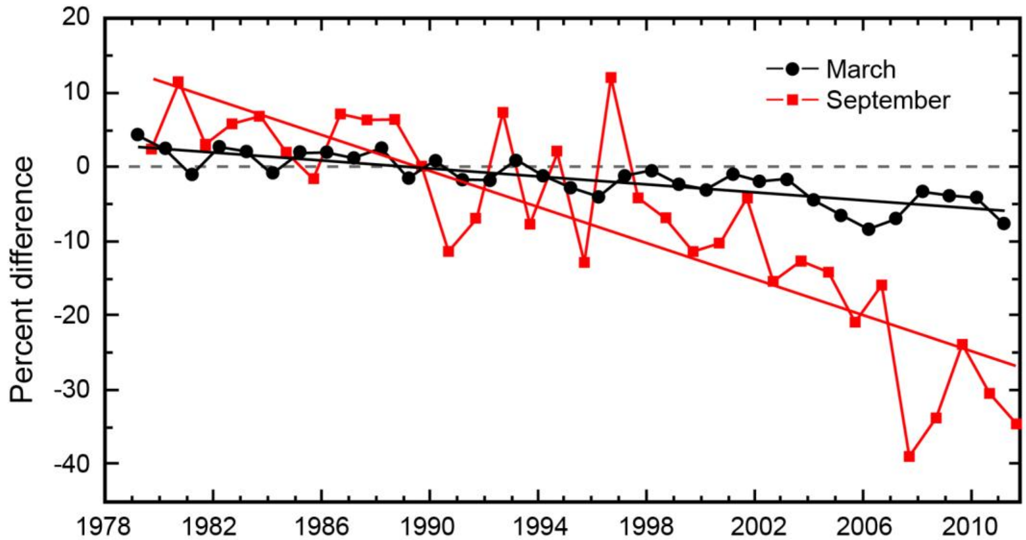


Figure 29. Time Series of the Percentage Difference in Ice Extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) Relative to the Mean Values for the Period 1979-2000.

Based on a least squares linear regression for the period 1979-2011, the rate of decrease for the March and September ice extents is -2.7% and -12.0% per decade, respectively (Source: Perovich et al., 2011).

4.6 Glaciers, Ice Caps, Ice Sheets, and Sea Level Rise

Melting of glaciers, ice caps, and ice sheets is contributing significantly to sea level rise. However, there are large uncertainties on the precise amounts, due to measurement difficulties. In this section we parse the phenomenon into three components – glaciers and mountain ice caps, Greenland, and Antarctica – and review the literature that estimates the contribution of each to sea level rise.

Glaciers and mountain ice caps have the potential to contribute a total of 0.7 meters to global sea level (Allison et al., 2009), the smallest component of possible sea level rise. Until recently, estimates of mass balance have been derived by extrapolating sparse measurements. These estimates have generally shown an acceleration of mass loss from glaciers and ice caps from roughly 0.5±0.2 mm sea-level equivalent per year from 1950-2000 to roughly 1.1±0.2 mm sea level equivalent per year in the early 2000s. However, these estimates are subject to sample bias. The Gravity Recovery and Climate Experiment (GRACE) provides the opportunity to address the sample bias. Very recent estimates by Jacob et al. (2012) based on GRACE suggest that the average contribution from 2003-2010 is only 0.41±0.08 mm sea level equivalent per year. However, the retrieval algorithms from GRACE are still in development and are likely to change as researchers gain better understanding of limitations and biases in retrieval algorithms (Baur, 2012).

The Greenland ice sheet has the potential to contribute 6.6 meters to global sea level (Allison et al. 2009). As with glaciers and ice caps, precise estimation of trends in mass loss is difficult. As an example, recent estimates indicate that "net ice mass loss from Greenland has been increasing since at least the early 1990s, and that in the 21st century the rate of loss has increased significantly. Multiple observational constraints and the use of several different techniques provide confidence that the rate of mass loss from the Greenland ice-sheet has accelerated. Velicogna (2009) used GRACE satellite gravity data to show that the rate of Greenland mass loss doubled over the period from April 2002 to February 2009" (Allison et al., 2009). Moon et al. (2012) use a comprehensive set of velocity maps derived from satellite observations to show that there are large regional variations in flow rates across the ice sheet and conclude that contributions to sea level rise are likely to be substantially less than previously estimated based on fewer measurements.

Zwally and Giovinetto (2011) report that estimates of mass loss from the Antarctic ice sheet also vary widely. (By comparison to glaciers, ice caps, and the Greenland ice sheet, however, one estimate suggests that under conditions of high warming of up to 8°C, the Antarctic ice sheet could contribute 20 m to sea level rise). The IPPC AR4 and subsequent reports of net mass balance range from +50 to -250 Gt/year for the period 1992-2009. Estimates based on radar altimetry indicate more modest losses (+21 to -31 Gt/year) and estimates based on GRACE and input/output methods suggest losses that are significantly larger (-40 to -246 Gt/year). Zwally and Giovinetto offer a preferred estimate of net mass balance of -47 Gt/year for the period 1992-2001, but this estimate effectively ignores any acceleration in net mass balance since 2001 – a period of significant atmospheric and oceanic warming.

Church et al. (2011) report that observed sea level rise from 1972-2008 inferred from tide gauges alone (1.8±0.2 mm/year) and from a combination of tide gauges and altimeter observations (2.1±0.2 mm/year) agrees well with an estimate based on the sum of contributions (1.8±0.4 mm/year). While total change in sea level is likely to be modest over the next decade (~16-23mm), even a relatively minor change may be expected to amplify the impact of coastal surges associated with storms, especially when these surges coincide with high tide.

4.7 Summary

In summary, the climate of the past decade has been unusual. Global average surface temperature in each of the ten years from 2002 through 2011 ranked among the top 13 years in a 132-year instrumental record; this decade has also been marked by a number of high impact weather related disasters that include dramatic heat waves, fires, droughts, floods, and storms. These phenomena are occurring at a time marked by increasing warming from greenhouse gases, as evidenced by numerous scientific measurements. At the same time, natural variability as evidenced by active El Niño-Southern Oscillations, the Atlantic Multidecadal Oscillation, and other regional oscillations is also clearly part of the record. An abundance of evidence makes it clear that the intensity of recent unusual events exceeds normal expectations and that their extent is worldwide, affecting people where they live, where they draw upon fresh water resources, and where they grow food, impacting thus national security at a fundamental level.

4.8 References

Alexander L. V. et al., 2006; Global Observed Changes in Daily Climate Extremes of Temperature and Precipitation, Journal of Geophysical Research. 111, D05109, doi:10.1029/2005JD006290.

Allegre C, et al. 2012; No Need to Panic About Global Warming, Wall Street Journal. Opinion (January 26). Available on-line: http://online.wsj.com/article/SB10001424052970204301404577171531838421366.html.

Allison, I., Bindoff, N. L., Bindschadler, R. A., Cox, P. M., de Noblet, N., England, M. H., Francis, J. E., Gruber, N., Haywood, A. M., Karoly, D. J., Kaser, G., Le Quéré, C., Lenton, T. M., Mann, M. E., McNeil, B. I., Pitman, A. J., Rahmstorf, S., Rignot, E., Schellnhuber, H. J., Schneider, S. H., Sherwood, S. C., Somerville, R. C. J., Steffen, K., Steig, E. J., Visbeck, M., Weaver, A. J.; The Copenhagen Diagnosis, 2009. Updating the World on the Latest Climate Science. The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 60pp.

Bauer O. (2012); On the Computation of Mass-change Trends from GRACE Gravity Field Time-series, Journal of Geodynamics doi:10.1016/j.jog.2012.03.007.

Blunden, J., D. S. Arndt, and M. O. Baringer, Eds., 2011; State of the Climate in 2010. Bull. Amer. Meteor. Soc., 92 (6), S1-S266.

Brown S. J., Caesar J., Ferro C. A. T., 2008; Global Changes in Extreme Daily Temperature Since 1950, Journal of Geophysical Research. 113, D05115, doi:10.1029/2006JD008091.

Center for International Earth Science Information Network (CIESIN), Columbia University; United Nations Food and Agriculture Programme (FAO); and Centro Internacional de Agricultura Tropical (CIAT). 2005; Gridded Population of the World, Version 3 (GPWv3): Population Count Grid, Future Estimates. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw.

Chen, M., P. Xie, J. E. Janowiak and P. A. Arkin, 2002; Global Land Precipitation: A 50-yr Monthly Analysis Based on Gauge Observations, J. Hydrometeor., 3, 249-266.

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., van den Broeke, M. R., Monaghan, A. J., Velicogna, I., 2011; Revisiting the Earth's Sea Level and Energy Budgets from 1961-2008, Geophysical Research Letters 38, L18601, doi:10.1029/2011GL048794.

Fan, Y., and van den Dool, H., 2008; A Global Monthly Land Surface Air Temperature Analysis for 1948-present, J. Geophys. Res. DOI:10.1029/2007JD008470.

Freidman, T. L., 2010; Global Weirding is Here, New York Times. Op-Ed. (February 17). Available on-line: http://www.nytimes.com/2010/02/17/opinion/17friedman.html.

Gleason, K. L. et al. 2008; A Revised U.S. Climate Extremes Index, Journal of Climate. 21. DOI: 10.1175/2007JCLI1883.1.

Hansen, J., Sato, M., Reudy, R., 2012a; Perception of Climate Change, Proceedings the United States of America National Academy of Sciences doi:10.1073/pnas.1205276109 (August 6). Available on-line: http://www.pnas.org/cgi/doi/10.1073/pnas.1205276109.

Hansen, J., Sato, M., Reudy, R., 2012b; Perceptions of Climate Change: The New Climate Dice, available on-line: http://www.columbia.edu/~jeh1/mailings/2012/20120105_PerceptionsAndDice.pdf.

Hosking, J. R. M., 2009; "lmom—L-moments," R package version 1.5, dated November 29, 2009, initial package release July 3, 2008, Available on-line: http://www.cran.r-project.org/package=lmom.

Hosking, J. R. M., Wallis, J. R., Wood, E. F., 1985; Estimation of the Generalized Extreme-Value Distribution by Method of Probability Weighted Moments, Technometrics 27(3): 251-261 (August).

Jacob, T., Wahr, J., Pfeffer, W. T., Swenson, S., 2012; Recent Contributions of Claciers and Ice Caps to Sea Level Rise, Nature 482:514-518. doi:10.1038/nature10847.

Kaufmann, R. K., Kauppi, H., Mann, M. L., Stock, J. H., 2011; Reconciling Anthropogenic Climate Change with Observed Temperature 1998–2008, Proceedings of the National Academy of Sciences (July 5). doi: 10.1073/pnas.1102467108.

Leibensperger, E. M., et al., 2012; Climatic Effects of 1950-2050 Changes in U.S. Anthropogenic Aerosols – Part 1: Aerosol Trends and Radiative Forcing, Atmospheric Chemistry and Physics, 12, 3333-3348. doi:10.5194/acp-12-3333-2012.

Masters, J., 2012; Summer in March: More All-time March Temperature Records in U.S., Canada, Wunderblog. Available on-line: http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=2057.

Meehl, G. A., Arblaster, J. M., Fasullo, J. T., Hu, A., Trenberth, K. W. 2011; Model-based Evidence of Deep-ocean Heat Uptake During Surface-temperature Hiatus Periods, Nature Climate Change. DOI: 10.1038/NCLIMATE1229.

Meehl, G. A., et al., 2009; Relative Increase of Record High Maximum Temperatures Compared to Record Low Minimum Temperature in the U.S., Geophysical Research Letters. 36, L23701, doi:10.1029/2009GL040736.

Monfreda, C., Ramankutty, N., Foley, J. A., 2008; Farming the Planet: 2. Geographic Distribution of Crop Areas, Yields, Physiological Types, and Net Primary Production in the Year 2000, Global Biogeochem. Cycles, 22, GB1022, doi:10.1029/2007GB002947.

Moon, T., Joughin, I., Smith, B., Howat, I., 2012; "21st-Century Evolution of Greenland Outlet Glacier Velocities," Science 336:576-578 (4 May).

Murphy, D. M., et al. 2009; “An Observationally Based Energy Balance for the Earth since 1950,” Journal of Geophysical Research 114, D17107, doi:10.1029/2009JD012105.

National Climatic Data Center, 2011. “Billion Dollar U.S. Weather/Climate Disasters.” National Oceanic and Atmospheric Administration. Available on-line: http://www.ncdc.noaa.gov/oa/reports/billionz.html.

National Climatic Data Center, 2012; State of the Climate Global Analysis Annual 2011. National Oceanic and Atmospheric Administration. Available on-line: http://www.ncdc.noaa.gov/sotc/global/2011/13.

National Oceanic and Atmospheric Administration, 2012. Extreme Weather 2011: A year for the record books. Available on-line: http://www.noaa.gov/extreme2011/.

NOAA, 2012; State of the Climate National Overview: March 2012. National Climatic Data Center. Available on-line: http://www.ncdc.noaa.gov/sotc/national/2012/3.

NOAA Mauna Loa Observatory, 2012; http://www.esrl.noaa.gov/gmd/ccgg/trends/.

Perovich, D., et al., 2011; “Sea-Ice,” in Richter-MJ., Jeffries MO, Overland JE, Eds., 2011: Arctic Report Card 2011, http://www.arctic.noaa.gov/reportcard.

Report Card 2011; http://www.arctic.noaa.gov/reportcard.

Rohde, R., Muller, R., Jacobsen, R., Perlmutter, S., Rosenfeld, A., Wurtele, J., Groom, D., Curry, J., Wickham, C., 2012; “Berkeley Earth Temperature Averaging Process,” Journal of Geophysical Research (submitted). Available on-line: http://berkeleyearth.org/pdf/methods-paper.pdf.

Romanovsky, V. E., Smith, S. L., Christiansen, H. H., Shiklomanov, N. I., Drozdov, D. S., Oberman, N. G., Kholodov, A. L., Marchenko, S. S., 2012: [The Arctic] Permafrost [in “State of the Climate in 2011”]. Bull. Amer. Meteor. Soc., 93 (7), S137-S138, 2012.

Romanovsky, V. E., personal communication, November, 2012.

Sheffield, J., Wood, E. F., 2008; “Global Trends and Variability in Soil Moisture and Drought Characteristics, 1950–2000, from Observation-Driven Simulations of the Terrestrial Hydrologic Cycle,” Journal of Climate, 21:432-458, DOI: 10.1175/2007JCLI1822.1.

Stroeve, J. et al., 2007; Arctic Sea Ice Decline: Faster than Forecast, Geophysical Research Letters 34, L09501.

Sueng Ki M. et al., 2011; “Human Contribution to More-intense Precipitation Extremes,” Nature. 470:378-381 (February). doi:10.1038/nature09763.

Velicogna, I., 2009; Increasing Rates of Ice Mass Loss from the Greenland and Antarctic Ice Sheets Revealed by GRACE, Geophysical Research Letters 36, L19503.

Walton, G., Weather Channel vis personal communication with Jerry Meehl, 2012.

Wickham, C., Rohde, R., Muller, R., Wurtele, J., Curry, J., Groom, D., Jacobsen, R., Perlmutter, S., Rosenfeld, A., 2012; “Influence of Urban Heating on the Global Temperature Land

Average Using Rural Sites Identified from MODIS Classifications," Journal of Geophysical Research (submitted). Available on-line: http://berkeleyearth.org/pdf/uhi-revised-june-26.pdf.

Wild M., 2009. "Global dimming and brightening: A review" Journal of Geophysical Research 114, D00D16, doi:10.1029/2008JD011470.

Wild M., 2012; "Enlightening Global Dimming and Brightening," Bulletin of the American Meteorological Society 93:27-37 (January). doi: http://dx.doi.org/10.1175/BAMS-D-11-00074.1.

World Meteorological Organization, 2011; Weather Extremes in a Changing Climate: Hindsight on Foresight, WMO-No 1075. ISBN: 978-92-63-11075-6. Available on-line: http://www.wmo.int/pages/mediacentre/news/documents/1075_en.pdf.

Zwally, H. J., Giovinetto, M. B., 2011; "Overview and Estimates of Antarctic Ice Sheet Mass Balance Estimates: 1992-2009, Surveys in Geophysics DOI 10.1007/s10712-011-9123-5.

5 Expectations for the Near-term Future

In the coming decade, one can expect to see patterns of extreme weather analogous to those of the recent past and potentially getting stronger, since these events are driven by a combination of internally generated natural variability and secular increases in warming that will likely persist. This expectation is based on statistical analysis of the observational record, physical understanding, and the general guidance provided by modeling. Local climate conditions will dictate what might be expected in specific regions of interest. Changes in extremes include more record highs and fewer but stronger tropical cyclones, wider areas of drought and increases in precipitation, increased variability, Arctic warming and attendant impacts, and continued sea level rise as greenhouse warming continues and even accelerates from expected aerosol reductions. Continuing and stronger extreme conditions combined with rising societal vulnerability are of national security concern both on a global and regional scale. Improvements in forecasts will require better observations combined with improved and regionally focused forecast models.

5.1 Introduction

Section 3 has summarized the science underlying the changing behavior of the climate system. In addition to its response to patterns of natural variability on a range of different time and space scales, the climate is warming. The warming is driven by a global imbalance in energy resulting from the ongoing increase in the concentration of greenhouse gases, offset partially by a contribution to cooling by aerosols. As a consequence of its warming, it is also capable of holding more water vapor. Section 4 has shown that there has been both warming and an increase of extreme weather around the world over the past decade relative to the past century.

Our goal here is to examine expectations regarding extreme events in the near term that can provide useful guidance in policy making. We recognize that the observational record has uncertainties associated with temporal and spatial coverage as well as accuracy of measurements, and that present numerical models can at best provide only approximate solutions. Thus we focus here on using insights gained from statistical analysis and physical understanding, past experience, as well as model input, as a basis for our conclusions. The conclusions are based both on a review of recent literature on the subject and on the comprehensive survey presented in the IPCC Special Report on "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" (IPCC SREX, WMO/UNEP, 2012).

The recent global increase of extreme events, as documented in Section 4, leads us to ask whether this increase will persist and what other changes can we likely expect, with the knowledge of how weather and climate have historically evolved, and with the understanding we have of greenhouse drivers. Without externally produced changes in atmospheric composition, it is a fair assumption to expect that we will see a range of events in the future that are like what we have seen in the past. However, with increased warming, it is likely that the effects on extreme weather as observed in recent years will continue to intensify. More detail on what we can reliably expect and what remains uncertain is provided below.

To predict beyond the deterministic forecasting limit of about 2 weeks we need information not only on what kind of climate norms we may expect in the next decade, but also on patterns and modes of natural variability. For some of these modes, such as El Niño-Southern Oscillation (ENSO), we have a good understanding of how they evolve and affect society. For others, such as the North Atlantic Oscillation (NAO), our knowledge is more limited. One thread running through the discussion here is the need for better understanding of the impact of ENSO, NAO, and the many other modes of natural variability, and to what extent these patterns change as greenhouse warming interacts with natural variability.

The overall circulation of the atmosphere with its various meridional winds, jets, and vertical circulation cells is summarized in the box below. The discussion is ordered by spatial scale:

CHANGES IN THE LARGE-SCALE FEATURES OF THE ATMOSPHERE
Overall warming and increased moisture: resulting from net positive addition of energy to the planet, due to a combination of increases in greenhouse gases and reductions in aerosols, will lead to more record highs, fewer record lows, more heat waves and wildfires, and a stronger hydrological cycle leading to more variability, more water per storm, and more droughts.
Expansion of the Hadley cell circulation: will widen areas of drought around the world in the sub-tropics with attendant increases in precipitation at higher latitudes.
Warming in the Arctic: leading to reduced sea ice in summer could favor more severe winter outbreaks in the U.S. and Europe. The decrease in the overall gradient of temperature between mid and high latitudes is consistent with a decline in the strength of the polar jet.
CHANGES IN REGIONAL IMPACTS
El Niño-Southern Oscillation and other natural oscillations: near-term climate variability will be largely dominated by ENSO. These patterns could be intensified and either enhance or mask changes due to GHG/Aerosols.
Impacts on monsoonal circulation: uncertainties are large here, and increased numbers of extreme events appears to decrease predictability. Models are unreliable, but a common pattern is likely to be an increase in extreme precipitation.
Arctic ice cover: expect acceleration of melting and earlier summer opening to navigation of the Arctic ocean than models predict, possibly in less than two or three decades.
Sea level: will continue to rise, expected to accelerate. Impacts will vary around the world.
CHANGES IN SMALL-SCALE FEATURES OF THE ATMOSPHERE
Fewer but stronger tropical cyclones: a more favorable heat and moisture environment for thunderstorms and tornadoes, but forecasts of numbers and locations uncertain
Simultaneity of extreme events: clustering in time and space can produce disproportionate impacts. With warming, there will be more sequential heat events. With the expectation of more storms and droughts, it is likely, but not certain, that there will be more simultaneous such events around the world. Persistence and blocking are key elements of regional forecasts, but uncertainties in forecasting are high

THE CIRCULATION OF THE ATMOSPHERE

The circulation of the atmosphere is driven by the heat from the sun, constrained by the rotation and geography of the Earth, influenced by its chemical composition and water in many forms, and affected by conditions on land and ocean. On a global scale, it consists overall of steady horizontal trade winds and vertical Hadley convection cells in the tropics, unsteady westerlies in the mid-latitudes, a jet stream, and polar circulation. Variability in these large-scale patterns is evident, having time scales of months to decades and even longer. On a regional and local scale, the circulation is dominated by weather patterns that have variability ranging from days to weeks and longer. (Figure 30 below from Lutgens and Tarbuck, 2001)

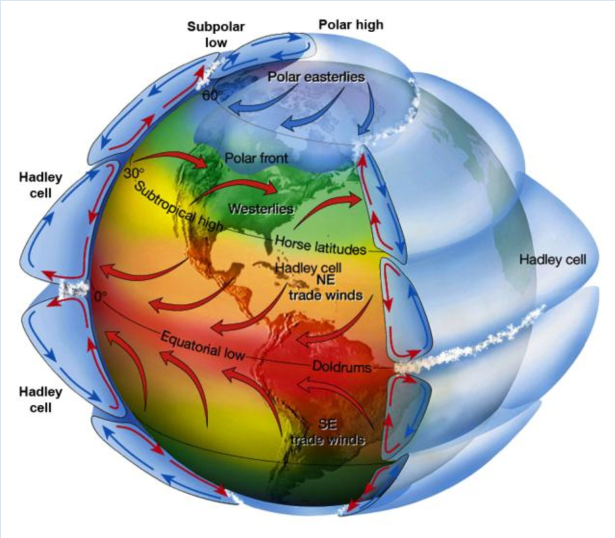


Figure 30. Atmospheric Circulation.

Today, with satellites monitoring the basic state of the atmosphere, a dense set of surface based data collection systems, and comprehensive numerical models, meteorologists are able to provide accurate forecasts of up to a few days, but still short of the deterministic limit of about two weeks. Beyond that time period, there is some skill and useful forecast ability based mainly on what is known about the internal variability of the atmosphere and how the atmosphere responds to slowly changing boundary conditions such as sea surface temperature, soil moisture, vegetation, and sea ice. External effects such as changes in solar radiation, changes in atmospheric composition from human-induced greenhouse gases and aerosols, and volcanoes also affect the atmosphere. Although many of these longer term atmospheric changes have a quasi-periodic behavior, seeming to oscillate from one state to another and then back again, there are also abrupt changes from one regime to another that are hard to predict, but persist once they are in place. Over the past century, the atmosphere has exhibited many modes of variability superimposed on a long-term warming trend (see Section 5.2).

5.2 Change of the Large-scale Features of the Circulation

Overall Warming, Highs and Lows in Temperature, Heat Waves, and a Stronger Hydrological Cycle

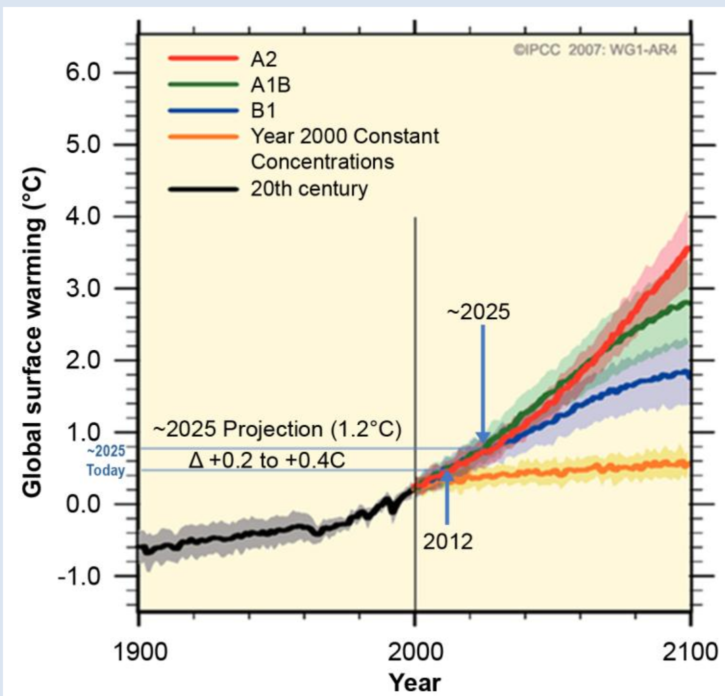
As discussed in Sections 3 and 4, the atmosphere in the troposphere is warming, and the stratosphere is cooling, consistent with the predictions of greenhouse gas forcing. The warming is greatest over land and at most high northern latitudes and smallest over Southern Ocean and parts of the North Atlantic Ocean, (IPCC 4th Assessment). The magnitude of warming is consistent with that expected by a combination of greenhouse gas/aerosol forcing. However, in terms of attribution, it should be noted that the past 15 years have been a time of increased ENSO activity, and thus it is possible that at least part of the observed warming could be due to this natural variability. But even if partially masked, increased warming is expected as the concentration of greenhouse gases increases and the concentration of aerosols is decreased.

The warming has an immediate influence on temperature highs and lows - driving observed weather to have more extreme or record highs and fewer record lows (Section 4). The higher frequency of higher nighttime temperatures also follows this trend. This trend is expected to continue into the future with an increase in the number of hot days and nights and decreases in the number of cold days, particularly including frosts. The increasing trend in heat waves is expected to continue, so all sectors of society sensitive to heat will be further affected.

From the increased temperatures, we can also expect an increase in the incidence of large wildfires. Paleological studies based on charcoal and pollen records indicate that periods of rapid changes of climate in North America were marked by increases in fire activity (Marlon et al., 2009). Analyses of fire records from the Western United States demonstrate a distinct increase in large fire frequency, duration, and seasons since the mid-1980s, mostly at locations where the confounding effects of land use and management can be ruled out. These increases are strongly associated with increased spring and summer temperatures and earlier spring snowmelt (Westerling et al., 2006). This relationship is further supported by statistical analyses showing strong correlations between measures of temperature and water deficit with area burned (Slocum et al., 2010; Little et al., 2009). Persistent droughts in a given location, more likely in a warmed climate, could lead to more wildfires (Fauria and Johnson, 2007).

GLOBAL WARMING IN THE COMING DECADES

The average decadal change in temperature from the 1950s to the last decade is estimated to be 0.89 ± 0.06°C (Rohde et al., 2012). Our analysis has shown that small positive changes in the global mean annual temperature are strongly correlated with increased prevalence of local annual mean temperature extremes. These extremes occur worldwide, not just in sparsely populated high latitude regions where the absolute change in temperature has been greatest, but in heavily populated and cultivated regions as well. The point is that changing climate globally can have major impacts in specific regions even though the global change may be modest. What can we expect in the next decade? The figure below shows the IPCC model based assessment published in AR4 in 2007, an assessment that is consistent with current projections. In the coming two decades we can expect modest warming, most likely on the order of 0.3°C independent of emissions pathway. This is, of course, barring unexpected volcanic disruptions that could force cooling temporarily, a major swing toward El Niño or other natural perturbation that may slow warming as appears to have occurred in the last decade, or diminishing industrial aerosols which may accelerate the warming process. The increased temperatures suggest the likelihood of persistent and possibly worsening of extreme weather in local regions over the coming decade.



"Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the [IPCC] scenarios A2, A1B, and B1, shown as continuations of the 20th century simulation [A2 most closely tracks the current emissions pathway]. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values" (IPCC, AR4, 2007).

With increased moisture in the atmosphere and constant relative humidity, there is expected to be an increase in frequency of droughts and of heavy precipitation. These are expected to affect natural ecosystems and crops as well as leading to increased water demand. This warmer pattern with stronger droughts and precipitation (see Figure 31) is fully consistent with expected impacts of greenhouse warming. Some aspects of the extremes have been predicted with some skill as the hydrological models of NCEP improve. Yuan et al. (2011) show how seasonal hydrological forecasts have improved. For example, the heat wave in the U.S. in summer 2011 was predicted a few weeks in advance (Luo, 2012). Continued progress will depend on improved modeling and more spatially detailed observations.

INCREASING NUMBERS OF RECORD HIGH TEMPERATURES

Meehl (2009) first documented the increasing ratio of record high temps to record lows as evidence for changing extremes in a warming climate. New evidence shows that for the first decade of this century that ratio had risen to about 2 to 1 for the U.S. and in Australia (Trewin, 2012). Since 2010, the ratio has been about 3 to 1 for the U.S., and over the first six months of 2012 the ratio has been about 10 to 1 (Walton, 2012). It's unlikely that the ratio will stay that high for the rest of 2012, but the rapid increase does illustrate how unusual this year has been for the U.S.

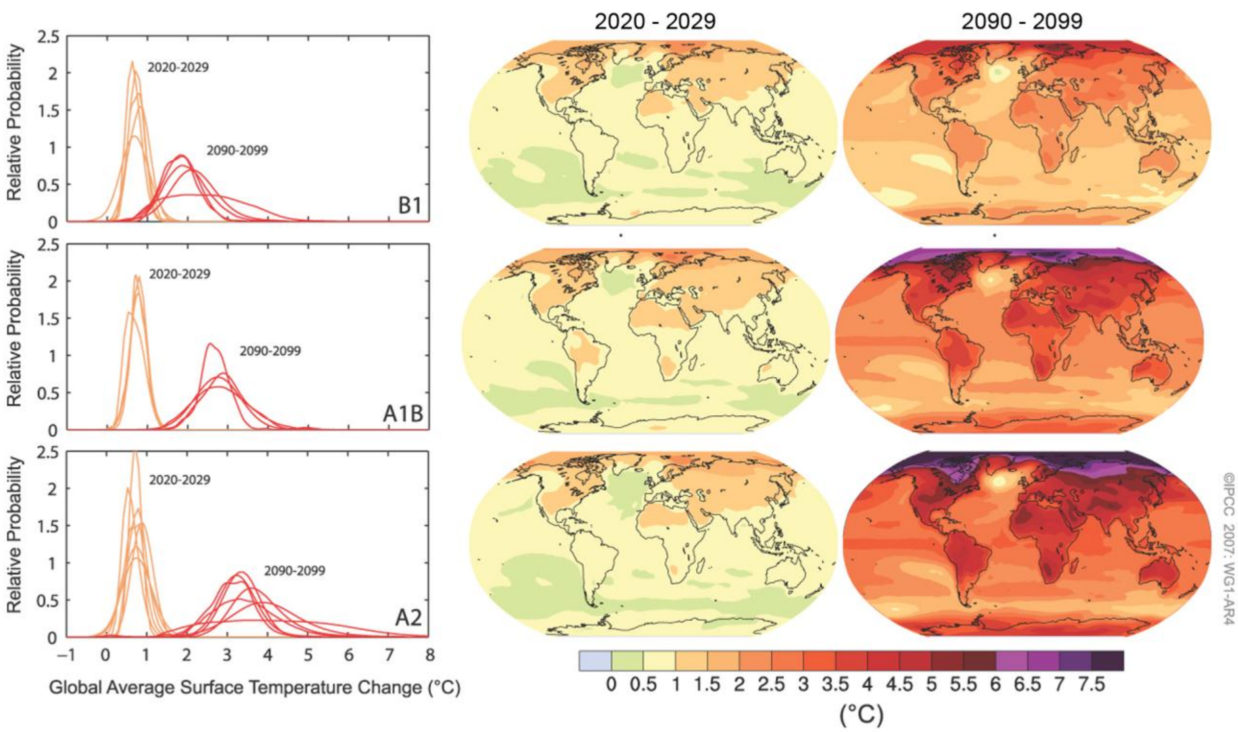


Figure 31. IPCC (2007) Projected Temperature Increases for the Years 2020-2029 and 2090-2099.

Effects of Aerosols

Aerosols impact global climate and are an important forcing agent for regional climate. Section 3 on the Basic Climate System has outlined the latest understanding of the impact of removing aerosols both globally and regionally. In summary, there are uncertainties in both the radiative properties and the concentration of aerosols, but enough is known to be able to say that the reduction of reflective aerosols will lead to warming. The IPCC (4^{th} Assessment) model study (Figure 32) showed that if all of the radiatively active aerosols were removed at one time, the resulting warming would be expected to exhibit geographical patterns focused in the northern hemisphere and over continents, a pattern different from that inferred for the greenhouse gas warming scenarios. Ongoing work is directed towards refining the geographic projections of where the largest impacts may be experienced in mid- to high-latitude regions such as Canada, Alaska, northeastern Europe, Russia, and northern China.

An important difference between aerosols and greenhouse gases is that there can be large changes in aerosols over relatively short distances and times. For example, desert dust aerosols over the North Atlantic are likely to have changed by a factor of 2 to 4 between the 1960s and 1980s (Prospero and Lamb, 2003). This is likely to have contributed to the Sahel drought, to changes in regional surface temperature over the tropics, and to changes in the globally averaged increase in temperature (Mahowald et al., 2010). It also appears likely that changes in North Atlantic tropical cyclone activity is strongly linked to variability in dust in the Saharan Air Layer (Evan et al, 2011, etc.), but the exact links are not fully understood.

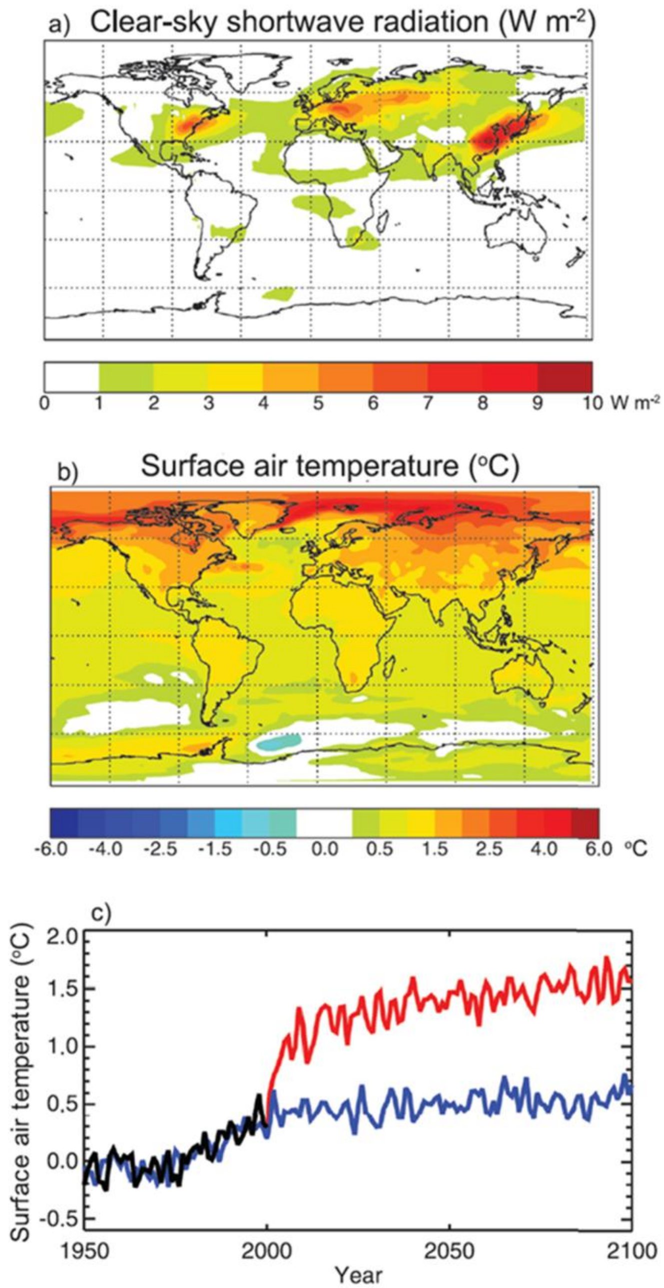


Figure 32. Effect of Removing the Entire Burden of Sulphate Aerosols in the Year 2000.

(Top) Annual mean clear sky TOA shortwave radiation (W m^{-2}) calculated by Brasseur and Roeckner (2005) for the time period 2071 to 2100 and (Center) on the annual mean surface air temperature (°C) calculated for the same time period. (Bottom) Temporal evolution of global and annual mean surface air temperature anomalies (°C) with respect to the mean 1961 to 1990 values. The evolution prior to the year 2000 is driven by observed atmospheric concentrations of greenhouse gases and aerosols as adopted by IPCC. After 2000, the concentration of greenhouse gases remains constant while the aerosol burden is unchanged (blue line) or set to zero (red line). The black curve shows observations (A. Jones et al., 2001; Jones et al., 2006).

Hadley Cell Expansion

Another illustrative example is the changing range of extreme weather facilitated by the expansion of the atmospheric Hadley cell, as discussed in Section 3. (See Figure 33 below for a schematic of Hadley cell expansion (Doster and Ferguson, 2008).

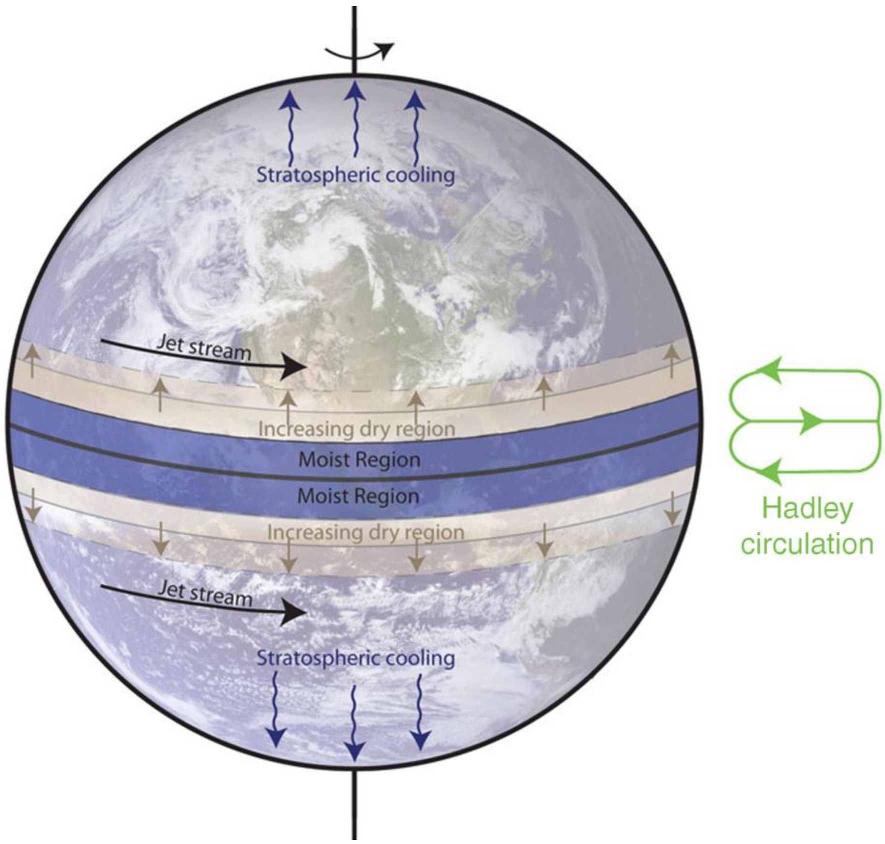


Figure 33. Hadley Cell Expansion.

Cooling of the stratosphere from ozone depletion high in the atmosphere and expansion of the Hadley cell from warming oceans are impacting the winter time tracks of the westerly winds over both hemispheres. This change could expand the world's deserts, meaning a potentially drier southwestern United States (Doster and Ferguson, 2008).

As the Hadley cell expands, the area of subsidence increases. This expansion is expected to continue and likely accelerate with more warming, thus leading to more droughts in the sub-tropical dry zones. Of particular concern are the semi-arid regions poleward of the subtropical dry belts, including the Mediterranean, the southwestern United States and northern Mexico, southern Australia, southern Africa, and parts of South America (see Seidel et al., 2007, 2008). A poleward expansion of the subtropical climate is likely to bring even drier conditions to these heavily populated regions. The impact on Southeast Asia is less severe and more localized with projected increases of precipitation due to the existing tropical climate, monsoons, and topography. With an expected precipitation decrease in the subtropics, there will likely be an attendant increase at higher latitudes, consistent with greenhouse forcing (Naik, 2012). Figure 34 shows the increase in precipitation (minus evaporation) at higher latitudes that is expected from modeling studies. Section 3 has noted that greenhouse warming models predict a change in the poleward expansion that is less than observed; clearly further work is necessary.

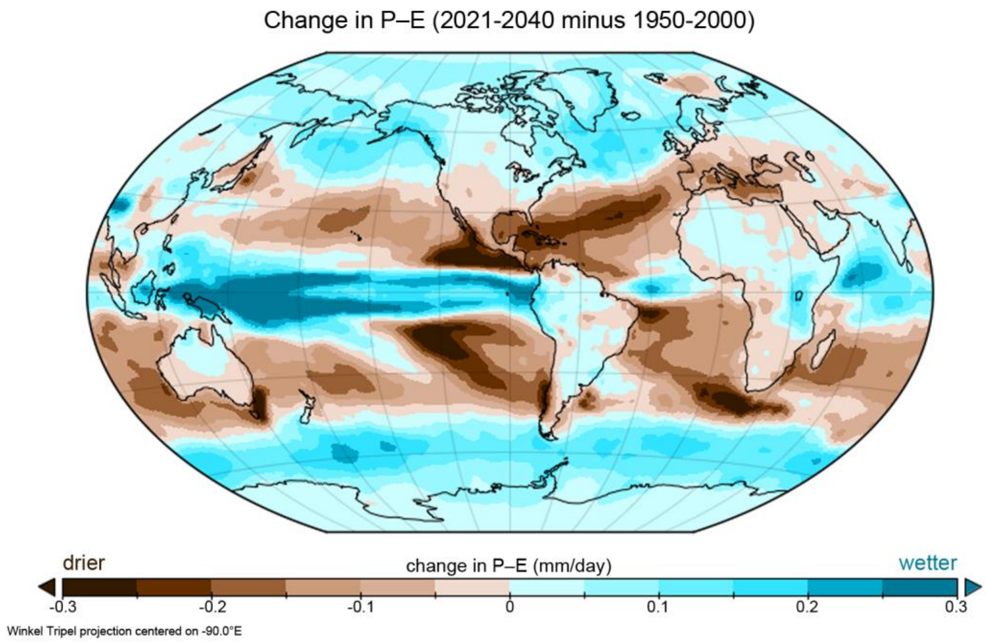


Figure 34. Predicted Drier Areas 2021 – 2040 (Based on Precipitation Minus Evaporation (P-E).

Results from 19 climate model simulations. P-E is the net flux of water at the surface that, over land, sustains soil moisture, groundwater, and river runoff. Figure by N. Naik.

Weakening of the North-south Gradient of Temperature, Poleward Shift of Jet Stream, Arctic Amplification

Greenhouse gas warming and ocean-ice feedbacks lead to the temperature increasing more at the poles than in the tropics. This differential in the northern hemisphere is known as "Arctic Amplification." In fact, as mentioned earlier in Section 3, a diagnostic study by Francis and Vavrus (2012) has used the fact that, during the past few decades, the Arctic has warmed about twice as fast as the entire northern hemisphere to conclude that summers with diminished Arctic sea ice were followed by large fluxes of heat and moisture entering the lower atmosphere during fall and winter. This process, together with enhanced polar fluxes of latent heat, appears to enhance Arctic warming.

As the poles warm preferentially, the temperature gradients from equator to pole thus decrease. Since the jet streams are dependent on the temperature gradient, it is expected that they in turn will weaken and show more variability. Changes have been observed already. For example, over the period 1979 to 2001, Archer and Caldeira (2008) found that in general the jet streams have risen in altitude and moved poleward in both hemispheres (Figure 35). In the northern hemisphere they found that the jet stream weakened, whereas there was a mixed signal in the southern hemisphere (other studies have related southern hemisphere changes to ozone depletion). The study did not determine the cause of these changes, but the expectation of a poleward shift of extra-tropical storm tracks with consequent changes in wind, precipitation, and temperature patterns is consistent with what is known about the impact of greenhouse warming. Hudson (2011) finds information from ozone patterns that tends to confirm this shift.

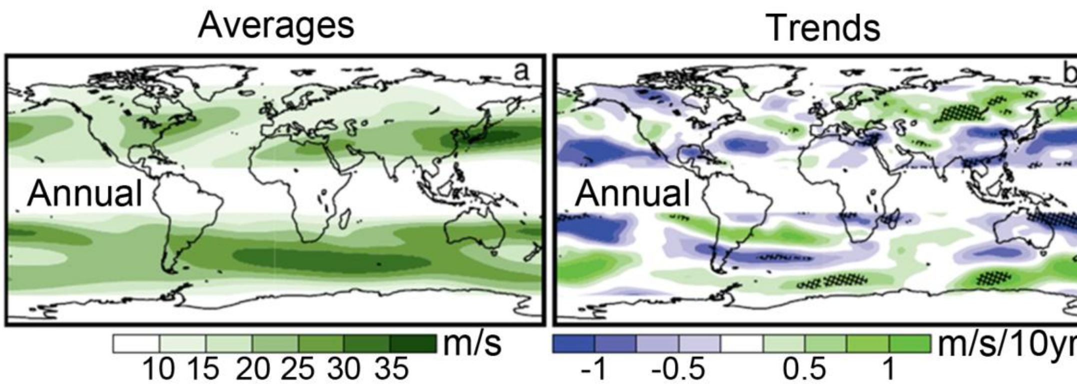


Figure 35. Average Jet Stream Speeds (left), and Strengthening and Weakening Trends (right).

Jet streams are generally strongest in the East, and have weakened over time in the Northern Hemisphere and the Sub-Tropical Southern Hemisphere. From Archer and Caldeira (2008), reproduced by permission of American Geophysical Union.

In the Arctic region, the trends and variability in surface air temperature are greater than for the globe as a whole (Serreze and Barry (2011)). They emphasize that the more rapid increase of temperature in the Arctic compared to the tropics is a key element of the climate system, with multiple intertwined causes including changes in sea ice extent, atmospheric and oceanic heat transport, cloud cover and water vapor, soot on snow, and increased black carbon aerosol concentrations. They conclude that the strong warming over the Arctic Ocean observed during the past decade which is clearly associated with reduced sea ice extent is just the most recent manifestation of Arctic Amplification (Serreze and Barry, 2011).

Figure 36. Negative Arctic Oscillation.

Image from Greene and Monger, 2012. Negative Arctic Oscillation conditions are associated with higher than usual atmospheric pressure in the Arctic and a weakening of the polar vortex and jet stream. Such conditions increase the probability of Arctic air masses spilling out into the middle latitudes and delivering severe weather outbreaks. A weakened jet stream is also characterized by larger amplitude meanders in its trajectory and reduction in the wave speed of those meanders.

What do we expect for the future? Much will depend on how the large-scale patterns of natural variability evolve. For example, Greene and Monger (2012) outline how a more open Arctic ocean could lead to an increase in Arctic atmospheric pressure and decrease in the latitudinal temperature gradient. This would favor the wintertime development of more negative Arctic Oscillation (AO) conditions, in turn favoring more severe winter weather outbreaks in the U.S. and Europe into the foreseeable future. They emphasize that the AO conditions have to be considered together with ENSO changes. The winter weather experienced will depend on a combination of AO and ENSO conditions: negative AO conditions can amplify the cold winters expected during El Niño years and can counter the warm winters expected during La Niña. Thus, while the dynamical links that connect climate forcing from the Arctic to mid-latitudes (these are called "teleconnections" – referring to climate anomalies being related to each other at large distances, typically thousands of kilometers) need further study, they appear to be an important driver of extreme weather.

Finally, we note that regarding the cold winters of 2010 and 2011, Hansen has expressed some skepticism about the use of AO for predictions, noting that: "Variability of the Arctic Oscillation (AO) index provides some insight into the significance of the prior two unusually cold winters. The AO index holds practically no predictive value; rather it is simply a convenient way of summarizing how the meteorological situation influenced the potential for movement of cold Arctic air. Unusually cold winters at middle latitudes tend to occur when surface pressure in the Arctic is high, because the weak zonal (jet stream) winds that occur along with high Arctic pressure tend to facilitate outbreaks of cold Arctic air into middle latitudes. The most extreme negative AO index in the record (more than a century long) occurred in the 2009-2010 winter and a less extreme but still strongly negative index occurred in the 2010-2011 winter." (Hansen et al., 2012).

5.3 Changes in Regional Impacts

El Niño and Other Natural Oscillations; Near-Term Climate Variability

El Niño-Southern Oscillation and other patterns of natural variability (also termed "oscillations") could either enhance or mask changes due to greenhouse warming. Our understanding of these patterns is that they typically have a broad reach and show some quasi-periodic behavior, but also will behave in a random manner. The spatial patterns of month-to-month and longer variability tend to have more spatial persistence than the day-to-day variability, leading to preferred spatial patterns. In the northern hemisphere these patterns are more prominent during winter than summer, but the Indian monsoon is an exception. In the tropics, most of the year-to-year variability of the atmosphere is forced by changes in sea surface temperature; models that include air-sea coupling can provide useful forecasts. The most prominent coupled mode of natural variability in the tropics is El Niño - Southern Oscillation (see Sarachik and Cane, 2010, for a detailed description). In the tropics, drought occurs in selected locations during the warm phase (El Niño; see Figure 37 below) and in the northern hemisphere drought occurs more frequently during the cold phase (La Niña).

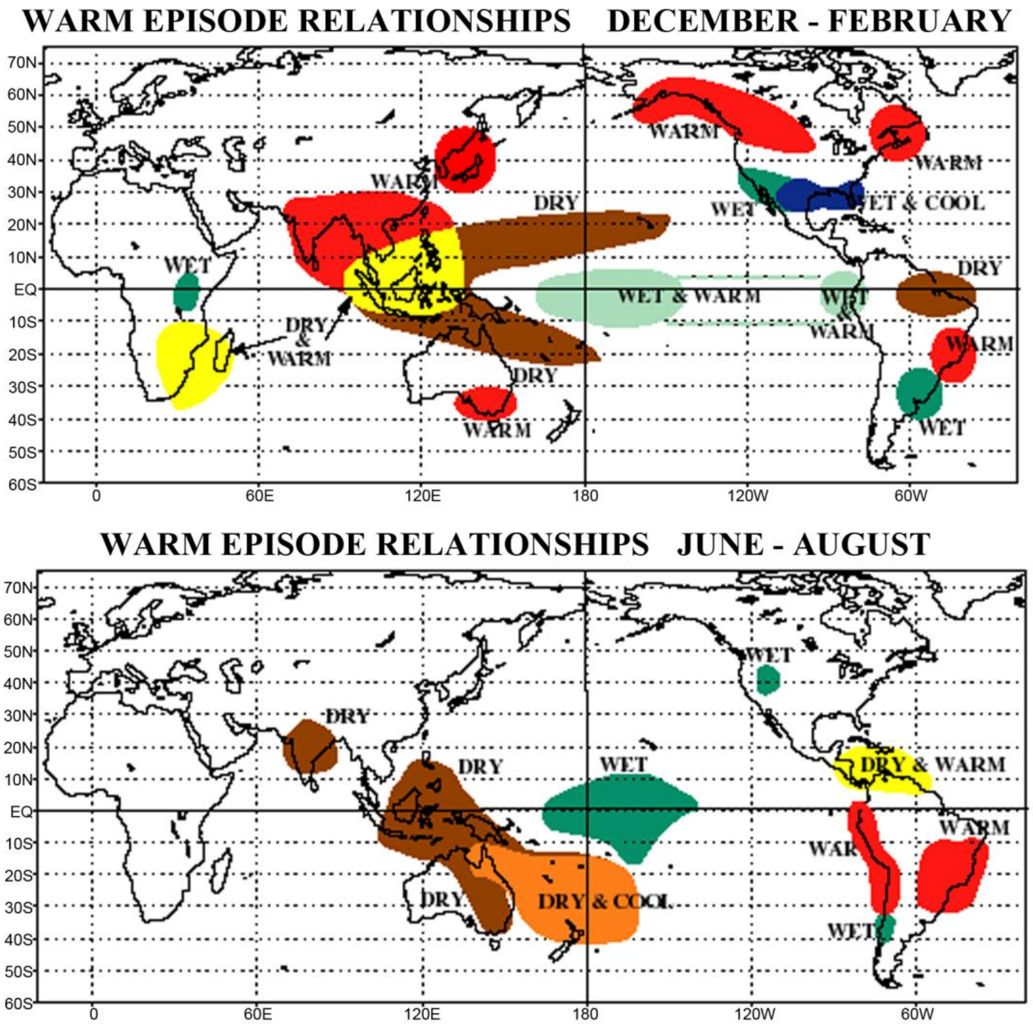


Figure 37. El Niño Impacts Are Seen Globally, and Are Expected to Be Enhanced with a Warmer, Wetter Atmosphere.

Warm episode relationships images from National Weather Service, 2012. Refer to the ENSO index provided in Figure 13.

There are also areas of increased rainfall during each of these phases, and the movement of water from ocean to land appears to have an impact on tropical sea level (Nerem et al., 2010). At extratropical latitudes in general, both boundary forcing and internal atmospheric dynamics make important contributions to year-to-year climate variability.

On longer time scales, known changes (e.g., seasonal heat, ocean surface temperature, sea ice, land use change) can provide “memory” on seasonal to interannual time scales and thus lead to skill in forecasting beyond two weeks. Changes that are difficult to monitor, for example soil moisture which goes up with rainfall and down with warming, can drive greater uncertainty on longer time scales. However, the quasi-periodic behavior of the more persistent changes affecting the atmosphere (ENSO, MJO, AMO, NAO, AO, PDO, and others; see Section 3) leads to hope that skill can be gained.

At this point, there is a growing body of evidence about how these various patterns evolve and interact (for example, ENSO and the NAO may be affecting the Indian monsoon, see below). The main point is that these are all internally generated climate phenomena of the climate system, and climate change is superimposed on these natural oscillations. If there is a La Niña - related drought, like the one in Texas in 2011, climate change that produces warmer and drier conditions on top of that turns it into a record drought, or, as the recent Bulletin of the American Meteorological Society paper states, that drought was 20 times more likely with climate change on top of the La Niña (Peterson et al, 2012).

Monsoons

Monsoons, the seasonal changes in atmospheric circulation and precipitation associated with the asymmetric heating of land and sea, occur in Africa, Asia, Australia, and even Europe, with the major ones being in West Africa and Asia-Australia. Given the importance of agriculture in the major monsoon countries, the focus of studies has been on changes in total and seasonal rainfall. For purposes of illustration, we will focus here on the Indian monsoon, but the conclusions are applicable in other geographical areas. A major portion of the annual rainfall over the Indian sub-continent is received during the summer monsoon season (June – September). The rainfall can be highly variable; a deficit leads to drought and an excess leads to floods. The total rainfall depends on the moisture flow and patterns of low pressure areas or monsoonal depressions over the area. These in turn are affected by interactions among local conditions, extra-tropical patterns, and teleconnections with, for example, sea surface temperature in various parts of the world.

For example, in Section 5.5 below, we describe how annual precipitation in the Indus, Ganges, and Brahmaputra River basins is dominated by the South Asian monsoon and present conclusions from an analysis of annual precipitation extremes restricted to the Indus, Ganges, and Brahmaputra River basins. These results show an increase across India in the prevalence of precipitation extremes of the past six years (2005-2011), consistent with the expected widespread increases in heavy precipitation events with increased warming (SREX). The prevalence of extremes during this period is greater than during the earlier period of extremes in the 1950s. We cannot rule out the possibility that the recent increase in the prevalence of annual precipitation may be driven by multi-decadal oscillations such as ENSO and NAO. However, the results are consistent with theory regarding greenhouse warming influences on the South Asian monsoon: that natural variability will be amplified and a common pattern will be a likely increase in extreme precipitation (SREX). If this trend continues, one would expect to see increased flooding throughout the region, consistent with recent large scale flooding along the Indus, Ganges, and Brahmaputra Rivers.

It is clear that there are statistically significant relationships between sea surface temperatures in the Pacific and Indian Oceans and the monsoon rainfall over India, and the combined effects of the sea surface temperature anomalies over both ocean basins are a critical factor for predicting the summer monsoon rainfall over India (Gadgil et al., 2005). There is a strong correlation between Indian monsoon rainfall and ENSO, in which a weak/strong monsoon is related to a warm/cold ENSO event. Since changes in monsoons are related at least in part to changes in sea surface temperatures, monsoon forecasts for the Indian subcontinent for either excess or deficit rainfall are likely to be improved by using the links to SST changes in the Indian and Pacific Oceans. Other large-scale oscillations, such as the NAO (see Ostermeier and Wallace (2003) on NAO/NAM trends) could also have an impact. The main point is that the NAO can shape regional-level precipitation during the peak months of the two main rainy seasons over the Indian subcontinent (Roy, 2011). However, there are distinct spatial variations in the response of regional-level rainfall to the monthly NAO index.

Globally, there is little consensus in model projections regarding the sign of future changes in monsoon circulation and rainfall (SREX, 2011). The models fail to capture the detailed spatial structure of monsoon rainfall, and will need to be able to resolve cloud systems with embedded deep convection. In order to improve this understanding, recent studies have focused on the fact that changes in regional monsoons are strongly influenced by changes in the states of dominant patterns of climate variability including, in addition to ENSO, the Pacific Decadal Oscillation, the North Atlantic Oscillation/Northern Annular Mode, the Atlantic Multi-decadal Oscillation, and the Southern Annular Mode. Surface processes and land use change can also affect regional monsoons by affecting heat and moisture transfer (SREX, 2011).

Processes in the Arctic also appear to affect the Asian monsoon, probably through the NAO. Prabhu et al. (2011) have shown that a positive anomaly of the satellite-measured sea ice extent in the Kara and Barents Seas (KBS) in October projects increased monsoon rainfall, with a negative anomaly signaling drought. In addition, they found that one of the predictors of the summer monsoon rainfall, the NW Europe mean sea level pressure anomaly during winter, could possibly be foreseen three to four months ahead of time with knowledge of the October sea ice extent in the KBS region. The evidence so far is tenuous, but a teleconnection, if it exists, could prove promising for improving monsoon projections. Changes in aerosol direct and indirect forcing, by affecting the timing of rainfall, can also have an impact on monsoons (Meehl et al. 2008).

Arctic Warming and Sea Ice Melting

The amplification of warming in the Arctic as mentioned above leads to melting of the Arctic ice pack. Section 3 has noted that in recent years, the total cover has been declining. There are vigorous feedback processes taking place here, based on the fact that open water absorbs heat much faster than ice-covered water. It is notable that the ice cover is declining faster than models predict (Figure 38). This appears to be largely due to a combination of a warmer ocean, thinner ice, and black carbon on the surface as well as small scale ice processes such as the opening of leads, movement of the pack, and heat transfer. Given that warming is expected to continue in the Arctic, this accelerated melting is very likely to continue.

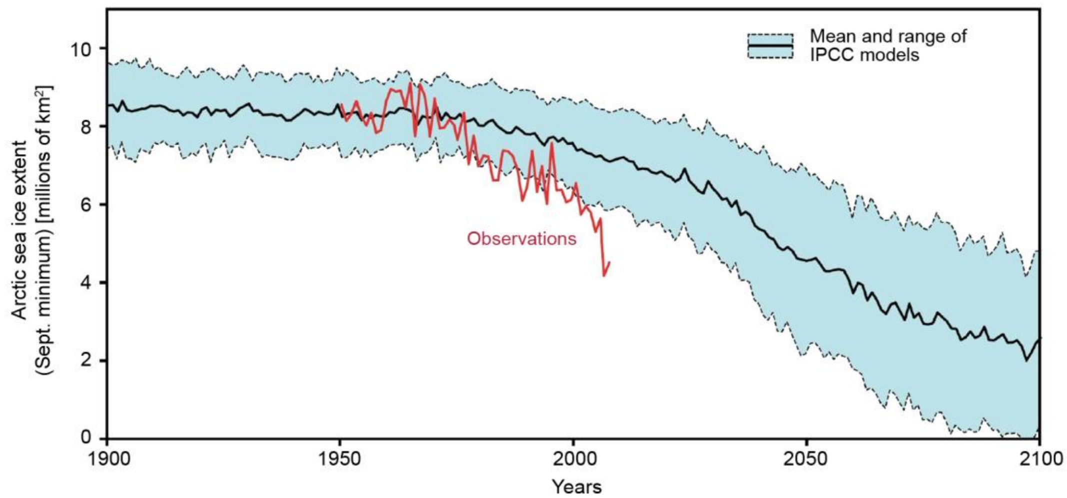


Figure 38. "Observed (red line) and Modeled September Arctic Sea Extent in Millions of Square Kilometers. The solid black line gives the ensemble mean of the 13 IPCC AR4 models, while the dashed black lines represent their range. From Stroeve et al. (2007), updated to include data for 2008. The 2009 minimum has recently been calculated at 5.10 million km^2, the third lowest year on record, and still well below the IPCC worst case scenario" (Source: Allison et al. 2009).

The changes in the Arctic have had dramatic impacts on not only the sea ice, but also on freshening of the upper ocean, and on biological productivity at the base of the food chain and loss of habitat for walrus and polar bears. Most importantly, the warmer weather has opened the Arctic to economic development through new shipping routes, mineral and fisheries exploitation, and competing claims for territory, all happening faster than expected a decade ago. These issues, combined with the fact that Arctic infrastructure is designed for the climate and ice-covered Arctic of the past, lead to the need for attention by the national security community.

Sea Level Rise

As the ocean warms, sea level rises. The currently observed rate is about 3 mm/year globally averaged, consistent with warming and melting of land-based ice. The actual rise varies around the world (see Figure 39; note strong effects in western tropical Pacific, and sea level decreases around the U.S. and western South America). The latest data on sea level compiled by the University of Colorado is shown in Figure 40 (Nerem et al. 2010). The trend is modulated by shorter-term changes on a seasonal to interannual time scale. For example, ENSO can cause sea level changes of up to about 5 mm from warming, cooling, and rainfall on land during a warm or cold period (Church et al., 2010; CSIRO, 2012).

It is reasonable to assume that at least for the near term, the current rate of change of about 3 mm/year would be the lower bound to use for estimating impacts – with increased rise if there is more rapid melting in Greenland or Antarctica (see Moon et al., 2012 for a cautionary note), and there could be noticeably higher levels in specific locations (see, e.g., Sallenger et al., 2012 for a potential impact on the U.S. East coast). To date, it has not been possible to detect a regional global warming signal on sea level (Meyssignac et al., 2012).

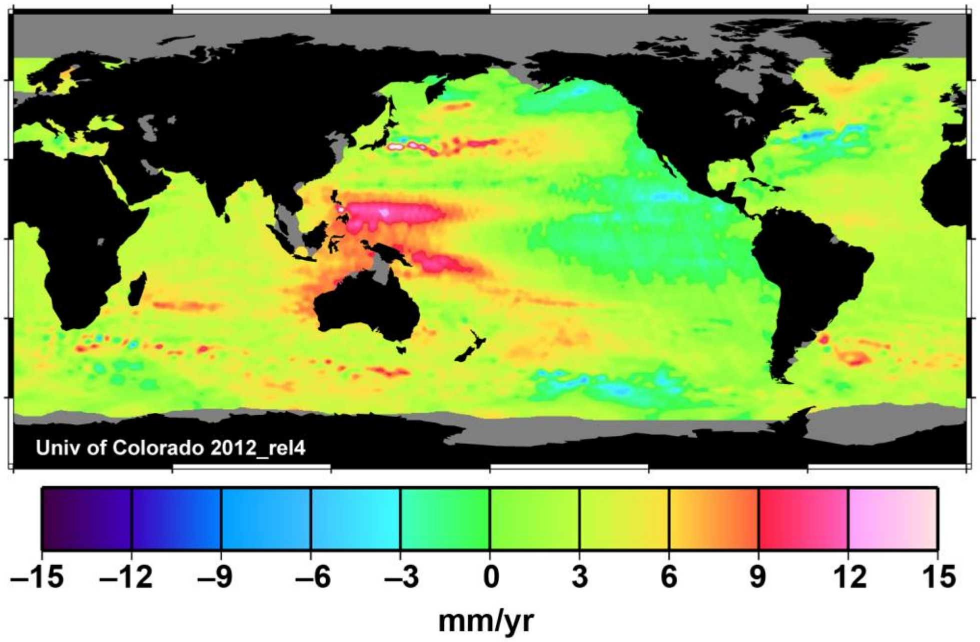


Figure 39. Global Distribution of Sea Level Trend (mm/yr) Derived from TOPEX/Poseidon and Jason-1 Satellite Altimeter Measurements from 1993-2012.

Figure from University of Colorado (http://sealevel.colorado.edu/content/map-sea level-trends).

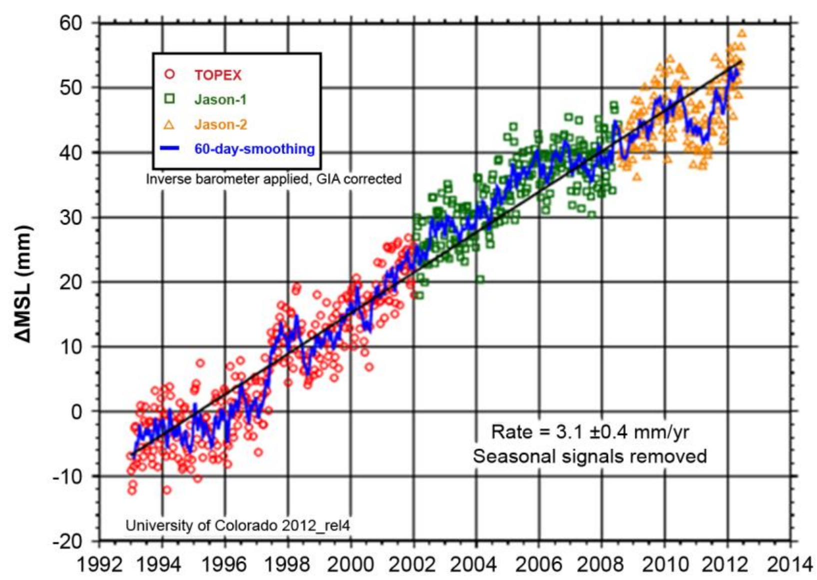


Figure 40. Global Average Sea Level Rise.

Image from University of Colorado, 2012. http://sealevel.colorado.edu/ (see Nerem, R. S., D. Chambers, C. Choe, and G. T. Mitchum; "Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions." *Marine Geodesy* 33, no. 1 supp 1 (2010): 435).

5.4 Changes in the Small-Scale Features of the Atmosphere

Fewer but Stronger Tropical Cyclones

Section 3 has noted that on the average we can expect fewer storms with stronger winds and more precipitation (see Knutsen et al., 2010, for a comprehensive review). The tendency for storms to have more precipitation per event is also documented in Section 2. However, the overall tendency for changes in numbers and intensity is not yet a robust signal because of the unreliability of the data. On a regional scale, the general circulation models do not yet have the resolution to simulate high intensity tropical cyclones. They cannot yet project where – even within which ocean basins –the changes will occur.

Trends that give useful insight have been constructed for Atlantic cyclones and use a measure known as the power dissipation index (PDI) that integrates the cube of the maximum surface wind at any given time in a storm over the duration of the storm. Figure 41 depicts the trend from 1949 through 2009, illustrating its correlation with sea surface temperature (SREX, 2012, p. 159; Emanuel, 2007). This time series shows a clear upward trend in the aggregate severity of Atlantic Tropical Storms since the mid-1980s, with current PDI levels about 4 times higher than those in the mid-1980s, and about two times higher than in the earliest portion of the record. Note that this analysis did not adjust for incomplete sampling of tropical cyclone frequency (Vecchi and Knutson, 2008), duration, or intensity. If these adjustments had been applied, they might have moved the earlier part of the record towards higher values (Knutson et al. 2010). A similar analysis has been performed for tropical cyclones in the western North Pacific. It, too, shows a marked increase in power dissipation, but is also subject to uncertainty due to limitations in the observational record for that region (Emanuel, 2007).

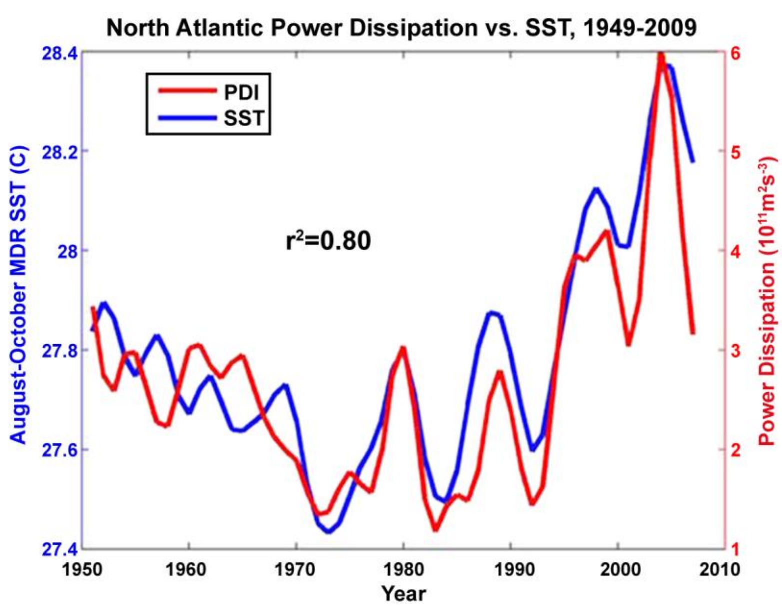


Figure 41. Low Pass Filtered Tropical Atlantic Sea Surface Temperature Correlated with the Power Dissipation Index for North Atlantic Hurricanes (Emanuel 2007, with data updated through 2009).

Image source: Knutson et al. 2010
(see also http://eaps4.mit.edu/faculty/Emanuel/publications/tropical_cyclone_trends).

In terms of warmer temperatures, tropical cyclones require the sea surface temperature to be at least 27^0C for the saturation vapor pressure to be high enough to provide enough latent heat for cyclone formation. However, as temperature rises, formation of cyclones is not simply related to sea surface temperature. The variability and trend of the power dissipation can be related to sea surface temperature and other local factors such as tropopause temperature and vertical wind shear. The data show that accumulated cyclone energy has been declining globally since reaching a high point in 2005 and in 2011 was at a 40-year low point (Maue, 2009). The period of heightened activity and later quiescence is not that different from past variability (SREX, 2012). The bottom line is that greenhouse warming will likely lead to stronger tropical storms, but that there will probably be fewer of them, but where this reduction will take place is not known.

In addition to tropical cyclones, thunderstorms and tornadoes are significant destructive events. Short-term prediction of tornadoes has improved markedly in the last few years, with recent forecasts giving at least a two-day notice for endangered areas. Greenhouse gas models do not yet have the capability to forecast specific locations of thunderstorms and tornoadoes, or even regions where these strong events might be enhanced or suppressed. Moreover, it is not clear from the observational data whether there have been changes in the frequency of such events. Nonetheless, it is useful in the sense that the future will be like the past to examine where the conditions have been right globally for significant thunderstorms and associated tornadoes.

Brooks et al. (2003) used the National Center for Atmospheric Research (NCAR)/United States National Centers for Environmental Prediction (NCEP) reanalysis system to create soundings and find environmental conditions associated with significant severe thunderstorms: hail at least 5 cm in diameter, wind gusts at least 120 km/hr, or a tornado of at least F2 magnitude (considerable damage) (Figure 42). Applying the relationships from the Eastern U.S. to Europe and the rest of the globe for a 42-year record from the second half of the 20th century, they found that favorable significant thunderstorm environments are concentrated in equatorial Africa, the central United States, southern Brazil and northern Argentina, and near the Himalayas.

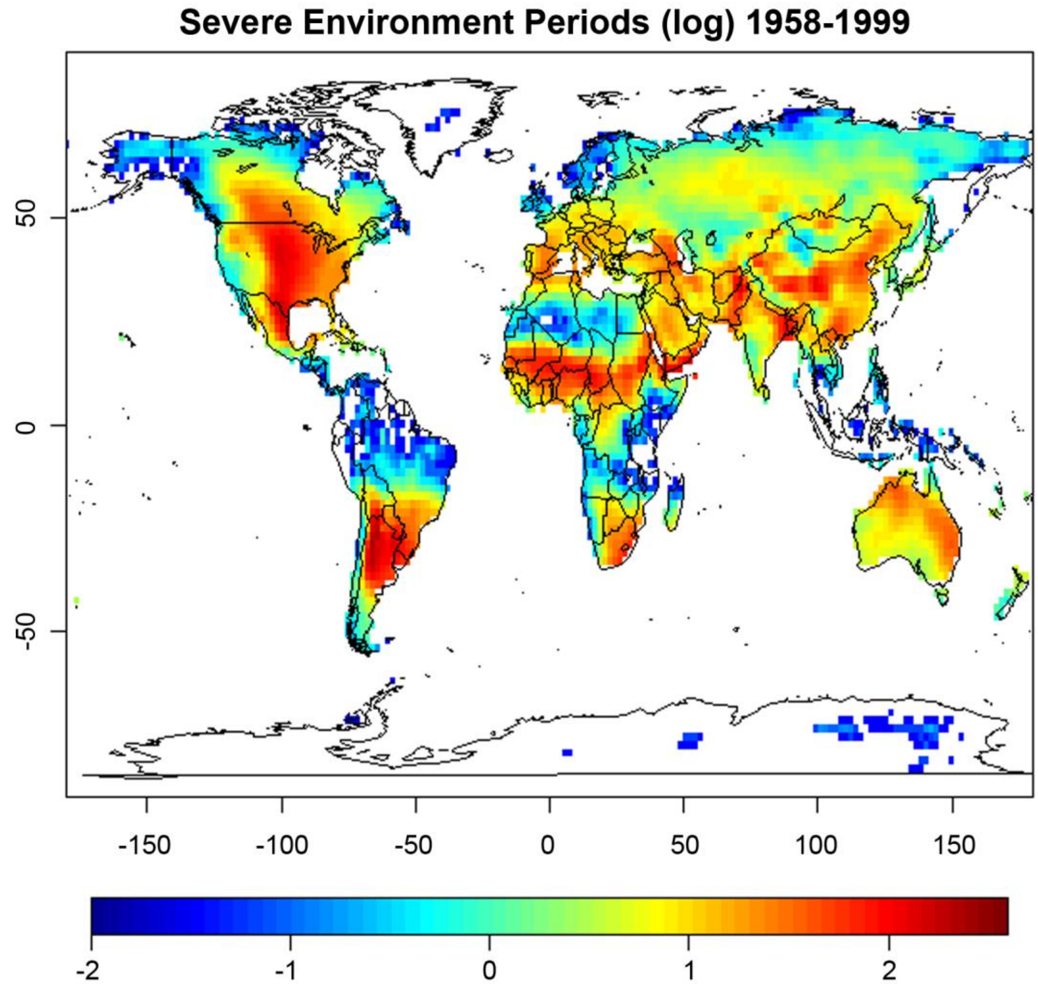


Figure 42. Days per Year with Favorable Severe Parameters, Showing Regions with the Greatest Frequency of Favorable Significant Thunderstorm Conditions.

Log scale; actual day numbers range from 0.01 to 100. (Brooks, et al. 2003).

Tornadic environments are by far the most common in the central United States (over 1,000 tornadoes recorded each year. Canada has about 100 per year. Other locations that experience frequent tornado occurrences include northern Europe, western Asia, Bangladesh, Japan, Australia, New Zealand, China, South Africa, and Argentina, with lesser areas in southern Brazil and northern Argentina (see Figure 43). Favorable significant tornadic environments are also found in France and east of the Adriatic. How the numbers of tornadoes will change with greenhouse warming is not understood. It is notable that the hot dry weather over the U.S. in 2012 has led to a strong decrease in the number of tornadoes.

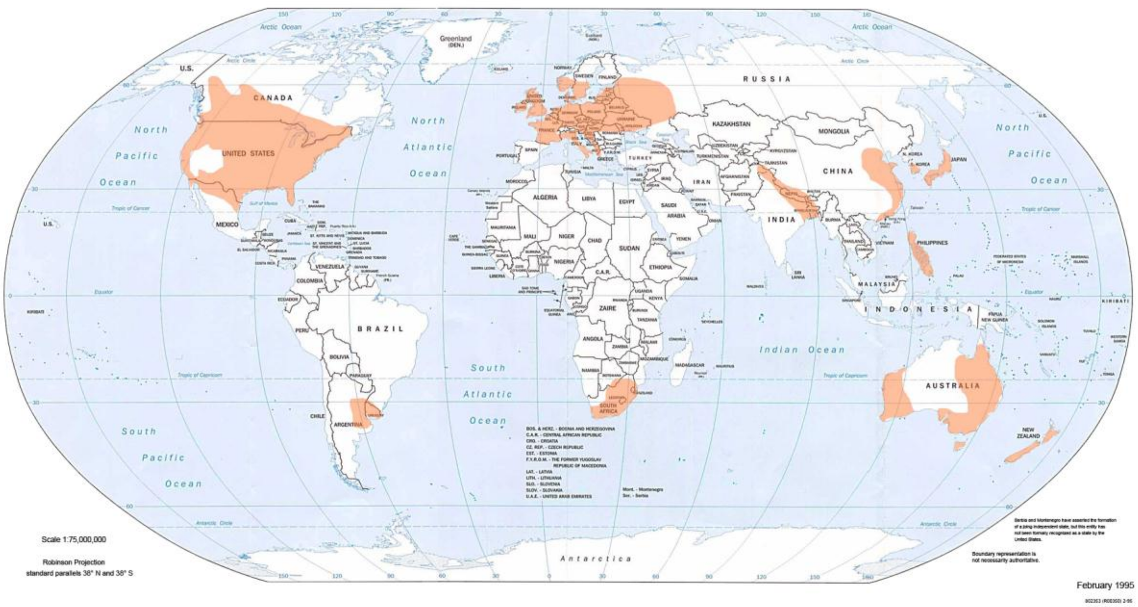


Figure 43. Regions of the World with Increased Likelihood of Experiencing Tornadoes.
http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html)

Persistence and Blocking: Regime Shifts

The non-linear turbulent physics of weather leads to a tendency for atmospheric weather patterns to change only very slowly, or "persist". As a consequence, it is often possible to use this persistence to forecast the continuation up to several days of an extreme event (e.g., floods, drought, above or below normal temperatures). For example, the air mass comprising a high pressure system, with anticyclonic circulation, has similar characteristics over the entire area it covers, and weather conditions can persist for days as the system moves over a locality. Such a system may take several days to pass over a given location in summer, while in winter it will move more rapidly. Therefore, in general, predictive skill is greater in summer than in winter (MacDonald, 1992). A good example of how persistence works is provided by Wallace and Hobbs (2006), who summarize the evidence on long-term droughts. Many of them appear to start and end with random fluctuations in atmospheric circulation which are sustained over long periods of time by positive feedbacks from the biosphere. They note that in the absence of healthy root systems ground water runs off more rapidly, and an extended period of above normal precipitation is required to restore it. The persistence of the 1930s drought is a good example, showing the impact of vegetation and ground hydrology. The climate regime that prevailed during the dust bowl appears to have perpetuated itself until a series of rainstorms made it possible for the vegetation to be restored. This abrupt but reversible regime shift between a climate conducive to agriculture and a more desert-like climate occurs frequently over semiarid agricultural regions such as the Sahel, northeast Brazil, and the Middle East. If the dry periods are sufficiently frequent or prolonged, then desertification occurs. Large-scale teleconnections through sea surface temperature changes are also important. Cane (in a private communication) has noted that it is possible to show that persistent droughts are closely linked to distant sea surface temperature changes.

Another example of persistence comes from the observation that the normal progression of middle latitude weather systems is sometimes interrupted by what are termed "blocking highs", leading either to continued rainfall or continued drought. There is useful persistence in blocking patterns, in that once such a pattern has lasted for about four days, it is likely to last twice as long as patterns that last only two days (Palmer and Hagedorn, 2006). The climatological location of blocking is shown in Figure 44 below (from UCAR COMET Program). Will blocking patterns change in a warming climate? At present, there is insufficient understanding of this highly non-linear process to venture a forecast. However, monitoring existing blocking could be useful in predicting weather impacts.

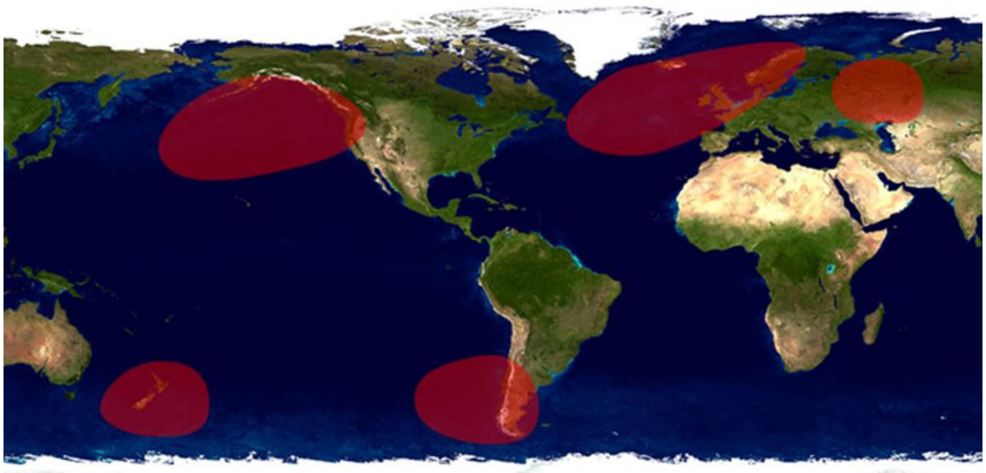


Figure 44. Climatological Location of Blocking Patterns (UCAR COMET Program).
(http://www.meted.ucar.edu/norlat/sat_features/blocking_patterns/overview.htm).

Simultaneous and Sequential Extreme Events Leading to Greater Impacts

Sequential extreme weather events can have a disproportionate effect on society, and thus any information about possible increased clustering in time or space would be valuable. Examples abound:

- Serial windstorms tracked across western Europe in January and February 1990 and again in December 1999 (Ulbrich et al., 2001)
- In summer 2007 there was a sequence of flooding events in the U.K.
- Temporal clustering of extra-tropical storms related to the variability of the NAO in recent years has been noted by Mailier et al. (2006).

Moreover, the aftermath of one extreme event may heighten the physical impact of successor events, and there can be strong feedbacks. SREX (2012) provides several examples. Other studies and events provide more examples:

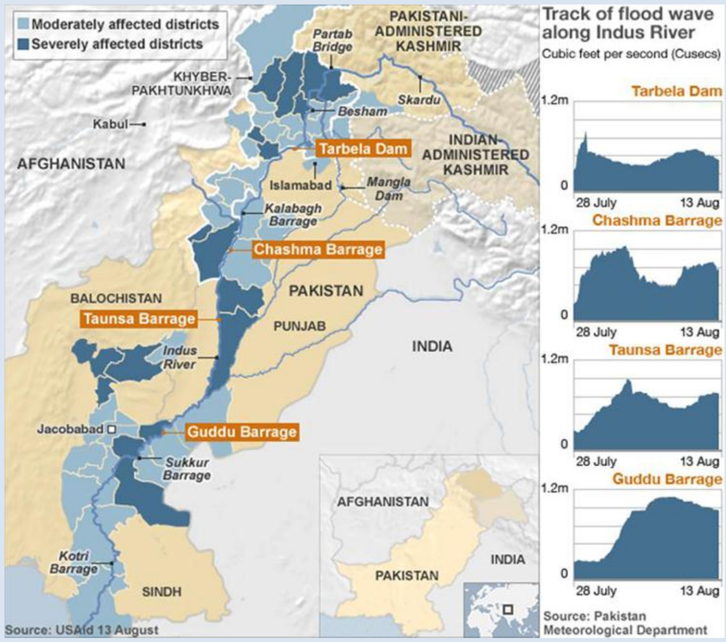
- High groundwater levels and river flows can persist for months, increasing the probability of a later storm causing flooding, as on the Rhine in 1995 (Fink et al., 1996).
- In the northeastern U.S. in 2011, when Hurricane Irene followed a rainy stretch that had left the ground soaked, resulting in serious flooding.
- A reduction in Arctic sea ice thickness preconditions more extreme reductions in the summer ice extent (Holland et al., 2006).
- Reductions in soil moisture can intensify heat waves (Seneviratne et al., 2006)
- Droughts following rainy seasons can turn vegetation into fuel for wildfires (Westerling and Swetman, 2003), which in turn promote soil runoff and landslides when the rains return (Cannon et al., 2001).
- Sarachik (2011) has suggested an alternative explanation for the major floods in Pakistan in 2010, building on links between two extreme events (see box below).

Whether there will be more sequential extreme events in a given place driven by global warming is not yet understood, but we do know that a globally warmed climate is likely to increase the probability of warmer summers in succession (Abarbanel et al., 1992). In addition, the probability of more events suggests the possibility of more sequential events, but there is no evidence from either physics or models to bolster this point.

SREX also notes that extremes can interact to reduce disaster risk. The wind-driven waves in a hurricane bring colder waters to the surface from beneath the thermocline; for the next month, any cyclone whose path follows too closely will have a reduced potential maximum intensity (Emanuel, 2001). Intense rainfall accompanying monsoons and hurricanes can bring great benefits to society and ecosystems; on many occasions it helps to fill reservoirs, sustains seasonal agriculture, and alleviates summer dry conditions in arid zones (e.g., Cavazos et al., 2008).

In summary, extreme events happening in sequence can cause larger impacts than any one event. Thus, extreme events happening at the same time around the world could be a national security issue requiring a response. For example, successive years of drought or sequences of storms are much less easily handled than such events in isolation, even by developed countries. Although we don't know whether or where sequences of storms will happen in the future, given our current understanding, we do know that large-scale oscillations, such as ENSO or the NAO, can guide storm tracks. Thus it will be important to monitor weather events and to watch for extreme events, particularly in vulnerable nations, to get early warnings for droughts, increased floods, and associated conflict. Blocking leading to a persistent pattern of rainfall or drought also has a large impact. Identifying areas of blocking and using persistence as a forecast tool can be helpful in regional forecasts. The highly non-linear nature of blocking has precluded any attempt to forecast the location and duration of blocking events, but efforts are continuing.

THE 2010 PAKISTAN FLOODS – AN EXAMPLE OF LINKS



One plausible explanation of what caused the extreme rainfall over North Pakistan beginning in late July of 2010 and continuing into August of that year is based on the fact that the Pakistan floods of 2010 overlapped in time with another equally unusual and extreme event: the Russian heat wave of 2010 (Grumm, 2010). A large-scale blocking high pressure zone established itself over eastern Europe and western Russia early in July, and temperatures in eastern Europe (Barriopedro et al, 2011) and Moscow started rising. By the end of July, maximum daytime temperatures were above 35°C in Moscow and stayed that high for the first 10 days of August. Almost every day set new records for the date. The extreme heat was accompanied by wide areas of drought, wildfires, and major crop losses (Trenberth and Fasullo, 2012).

The basic mechanism connecting the two extreme events (Hong et al, 2011; Lau and Kim, 2012) appears to be that the trough downstream (i.e., east) of the blocking high radiated tongues of high potential vorticity downward and southward. When the tongue reached the ground in the vicinity of North Pakistan (35°N) on July 27, it met and enhanced a monsoon surge and gave rise to extraordinary rainfall (Sarachik, presented at Washington, DC, Workshop 16-17 February, 2012). See also the upcoming NRC report “Assessing the Impacts of Climate Change on Social and Political Stresses” on the role of the synoptic pattern that set up the floods and the 2010 Russian heat wave; http://www8.nationalacademies.org/cp/projectview.aspx?key=49399.

5.5 Regional Trends and Expectations – Summary

General Issues

When discussing climate change, questioners often turn immediately to forecasts of near-term - months to a decade or so - regional effects. But today, specific forecasts for regional changes in weather and climate are limited in their skill at both ends of the spectrum. In the short term, deterministic weather forecasts are limited to at most two weeks, due to the dynamical and chaotic nature of atmospheric circulation and energy content and their influences on weather systems. In the long term, general circulation models provide guidance as to weather variable norms only on large, up to global, scales for periods of decades. Near-term regional forecasting, on the order of a month to a year and for scales the size of nations or smaller, is an emerging but yet immature capability.

Some success has been shown in describing ENSO effects in specific regions across the globe, with nine-month projections issued monthly by the NOAA Climate Prediction Center. Such techniques make use of robust features of changing climates, such as the natural variability of ENSO superimposed on warming and expected geographic expansion of heat waves and temperature extremes. But the forward vision of these models is limited, to around a year or less. Incorporation of additional ocean/atmospheric oscillations, such as the NAO or AMO, would provide useful insight into what might happen on a regional level in short-term forecasts, but is only just emerging and still lacks adequate observational data and definition. Our knowledge of the dynamical features of the sea surface, namely sea surface temperature and heat transfer, is also limited. This leaves decadal forecasting in a relatively uncharted zone, forcing us to rely on understanding the influences of robust features of the climate system, discussed in previous sections.

It is important to note that that on a regional scale and over a 20-year time frame, temperature trends are driven by internally generated natural variability, in addition to overall trends imposed by anthropogenic forcing. However, the features of near-term regional climates will evolve according to some of the basic physical traits of the climate system that we have discussed in preceding chapters. Thus, the regional forecaster will have to rely on a combination of techniques and will have to track changes closely in regions of special interest. The following reviews salient points made earlier in the document in the context of how they may guide near-term regional assessments.

Recent observations show more frequent extremes across the globe. A careful examination of recent weather events shows that extreme events, namely what were previously observed as 1 in 100 year events, now appear to be 1 in 20 year events or even more frequent. The time series are not long enough to provide the full statistical certainty one would wish, but the results are suggestive, and in combination with what we know about the physics of weather and climate, should be taken seriously in national security planning. It is likely that these extremes will continue to occur, both for temperature and for precipitation. It is important to note that in extratropical latitudes, the temperature anomalies associated with extreme events are much larger than the incremental temperature changes associated with global warming. For example, in

March of 2012 over much of the U.S., temperatures were in excess of 20°C above normal on many days. The contribution of global warming to this record warmth was about 0.8°C, or just a few percent of the total excess. Even in the absence of global warming, March 2012 would have been an extraordinary month in which many high temperature records were set. This occurrence, however, may have set the scene for further unusual conditions.

Heat extremes will have a significant effect on agricultural regions. The impact of temperature extremes on crop production has been well documented. Now with the likelihood of more hot days with record heat and precipitation changes, crop yields are more vulnerable. Maps of record highs, particularly in winter and in countries that are heavily agriculturally dependent, will help forecast later crop production (Battitsti and Naylor, 2009).

Global warming is accelerated by aerosol cleanup, especially in industrial regions. We know that increased concentrations of greenhouse gases in the atmosphere will inevitably lead to a warmer world. Because of uncertainties in understanding feedback processes in the climate system and cooling because of aerosols, it is not fully understood exactly how fast this warming in the atmosphere will occur. The warming could be accelerated by removal of aerosols, a process that is currently happening. Since removal of aerosol pollution is a policy goal in most countries, dictated by objectives to protect human health and the integrity of local environments, it is logical to expect an acceleration of warming and thus enhancement of the extremes we discuss here.

A stronger hydrological cycle will lead to more water per storm across the globe. The warming of the atmosphere means that it is capable of holding more water vapor. In recent years, individual storms have been observed to release more water. There is no reason to think that this trend will change. At the same time, we are seeing some increases in the number of droughts. The global data on the hydrological cycle from both ground measurements and satellite-based salinity measurements of the ocean, although not as comprehensive as the temperature data, show that the global water cycle is intensifying. We are seeing more rain and more droughts, and these are appearing at a rate faster than the current generation of climate models would predict. In any case, there will continue to be floods and droughts, and we can at least expect extremes of weather to persist.

Occurrence of sequential and simultaneous extreme events is likely to increase. Extreme events happening in sequence can cause larger impacts than any one event. Extreme events happening at the same time around the world could be a national security issue requiring a response. For example, successive years of drought or sequences of storms are much less easily handled than such events in isolation, even by advanced societies. Although at this point we are not able to predict exact sequences, we do know that a globally warmed climate is more likely to increase the probability of warmer summers in succession (Abarbanel et al., 1992). Although we don't know whether or where sequences of storms will happen in the future, given our current understanding, we do know that large-scale oscillations, such as ENSO or the NAO, can guide storm tracks. Thus, it will be important to monitor weather events and to watch for extreme events, particularly in vulnerable nations, to get early warnings for droughts, increased floods, and associated conflict. Blocking leading to a persistent pattern of rainfall or drought also has a large impact. Identifying areas of blocking and using persistence as a forecast tool can be helpful in regional forecasts. The highly non-linear nature of blocking has precluded any attempt to forecast the location and duration of blocking events, but efforts are continuing.

In short, while we are limited today in the use of decadal projections to forecast regional climate, a growing body of knowledge shows that the improvement of regional projections may well be possible.

- Aerosols decrease leads to increasing temperature. In particular, advance warning may well be given for temperatures to increase where aerosol pollution is likely to be reduced, for example over China, but this will require advances in our understanding of the regional sensitivity of climate to aerosol forcing.
- Tracking the NAO, ENSO, and other similar large-scale oscillations that guide storms could be helpful in identifying regions where clustering or sequences of storms are likely.
- Following the onset and evolution of ENSO, NAO, and other oscillations leads directly to geographic regions of vulnerability. For example, the El Niño phase of ENSO leads typically to droughts in Indonesia, with heavy rainfall in South America. It may also be that GHG warming leads to a positive NAO with attendant effects on temperature distribution and storm tracks.
- Links between or among extreme events, as noted with the Pakistan floods and the Russian heat wave, give insight into how these events begin and evolve. These links are not fully understood and need further exploration, but using the fact of the links and tracking changes could be valuable for regional forecasts.
- Monsoon forecasts for the Indian subcontinent for either excess or deficit rainfall currently have little skill, but are likely to be improved by using the links to sea surface temperature changes in the Indian and Pacific Oceans and other ENSO changes. Other large-scale oscillations, such as the NAO or changes in Arctic sea ice, appear to have an influence on the monsoon. Tracking these changes may help provide insights into rainfall changes. More work is needed with models to incorporate the right physical processes.
- Regarding techniques for near-term, regional forecasts, given what is known today about atmospheric processes, it is clear that the models can be guided by better and more comprehensive data. Coupled models together with input from high-resolution observing systems, including national technical means, may be able to make useful projections of what might happen in sensitive regions, such as the Arctic. For example, an early warning system might be developed based on where severe weather is now happening, and then using the knowledge of large-scale patterns to see if there is a possibility for compatible conditions to persist.

Specific Areas of Interest

Global expectations for a warmer climate, wetter in some areas and drier in others, with more extremes cannot be easily translated into specific near-term forecasts for any given region. Global climate models are designed to reproduce both long-term trends and observed modes of natural variability such as ENSO and NAO, and typically project climate change over roughly a century time frame. They do not yet adequately characterize many of the phenomena described above. As a result, it has not been possible to use those models for regional forecasts on the time scale of one or two decades. However, the new field of decadal climate prediction is providing new capabilities to address near-term climate change with initialized forecasts (Meehl et al., 2009). The models do provide an overall context in which we can examine regional trends based on physical insights such as the observed expansion of the Hadley cell.

This report presents trends in the prevalence of annual temperature, precipitation, and freshwater extremes in six regions with high national security relevance: the U.S.-Mexico Border, the Eastern Mediterranean, Southwest Asia, the Himalayas, and China. In general, the analysis of trends for specific regions is less conclusive than projections of long-term trends in extremes. The climate in these regions is controlled by a combination of patterns of long-term natural variability together with climate change impacts. When aggregating across many regions, each controlled in different ways by such patterns, there are clear trends toward greater prevalence of extremes. Furthermore, in regions that show prior periods with elevated prevalence of extremes, the current period of elevated extremes is significantly more pronounced. While not conclusive, these results are consistent with the understanding of large scale climate phenomena that amplify local patterns of natural variability.

The requirement that national security analysts have for regional information may be partially addressed by using rapidly improving seasonal forecast systems such as NOAA's Climate Forecast System (CFS) to routinely monitor regions for impending climate stress. These models have demonstrated improving skill at predicting temperature, precipitation, and hydrological extremes with up to nine months of lead-time. Efforts to construct climate models tuned to the decadal time scale are just beginning to be organized.

Mexico and Southwest United States

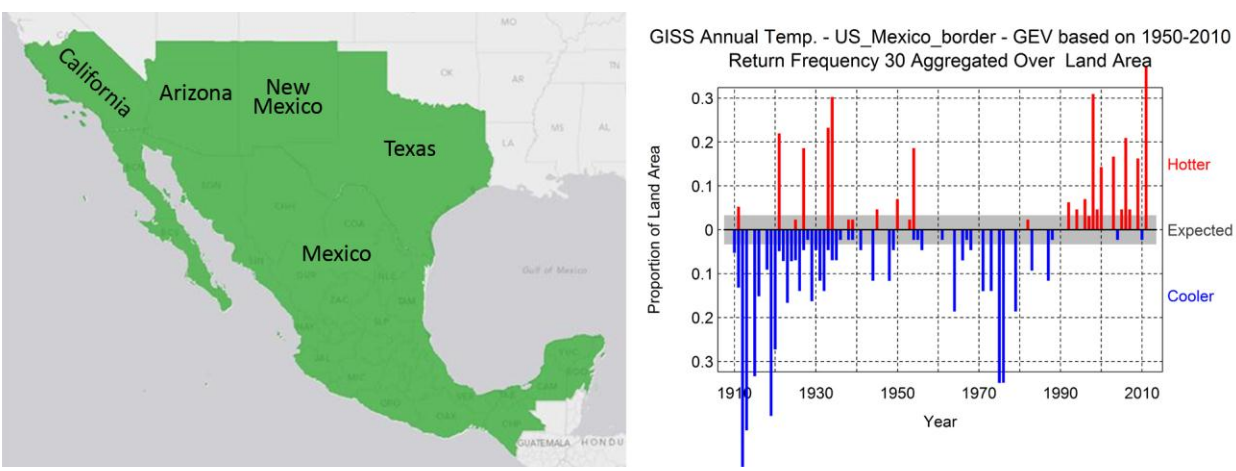


Figure 45. Trends in the Prevalence of Extreme Temperatures for Mexico and Southwest United States.

This chart depicts the fraction of land area in the region experiencing extreme annual average temperatures from 1910 to present. The red bars show the fraction of consistently measured land area experiencing hot anomalies defined as temperatures one would expect to see no more than once every 30 years using a 1950-2010 climatology. The blue bars show the fraction of land area experiencing similarly defined cold anomalies. The gray area shows the expected proportions given a stationary climate.

Figure 45 depicts the fraction of land area in Mexico and the Southwest United States experiencing extreme annual average temperatures from 1910 to present. The greatest prevalence of high average temperatures occurs in two periods: 1920-1934, and 1998-2011. The latter period includes the two years with most widespread occurrence of high average temperatures (1998 and 2011), has more high years than the earlier period (6 of 13 or 46% are above 0.1 vs. 4 of 14 or 29% in the earlier period), and exhibits much lower occurrence of low temperature anomalies than the earlier period. The periods from 1910 through 1932, and the mid-1960s through the 1980s, are characterized by widespread cool average annual temperatures. This particular analysis cannot discern whether temperatures in this region are dominated by a) natural variability, b) a warming trend, c) rapid regional industrialization that resulted in large emissions of aerosols from coal-fired power plants and the subsequent reduction in these emissions due to the Clean Air Act of 1990, or d) some combination of all three phenomena.

In the future this region is likely to be affected by the expansion of the Hadley cell as described earlier. One would expect a hotter, drier climate with attendant expansion of desert and arid zones. This region is also vulnerable to Pacific and Atlantic hurricanes. Some analyses suggest that these hurricanes will become less frequent but more intense and, therefore, more destructive.

Eastern Mediterranean Region

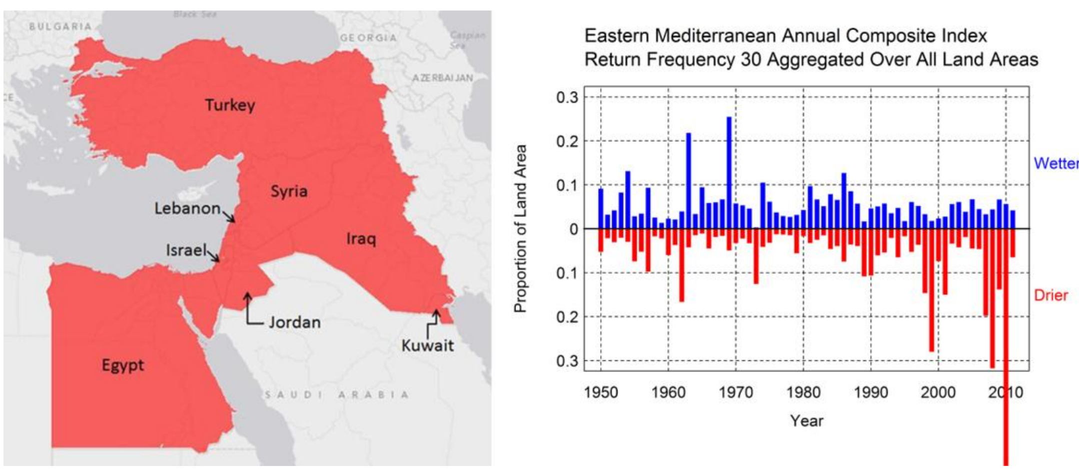


Figure 46. Trends in the Prevalence of Extreme Freshwater Deficits and Surpluses for the Eastern Mediterranean.

This chart depicts the fraction of land area in the region experiencing extreme freshwater deficits and surpluses from 1950 to present. The red bars show the fraction of land area experiencing freshwater deficits (meteorological droughts, agricultural droughts, or hydrological droughts) defined such that one would expect to see them only once every 30 years using a 1950-2010 climatology. The blue bars show the fraction of land area experiencing similarly defined freshwater surpluses (runoff or total blue water) that are often associated with large scale flooding.

The Eastern Mediterranean region (Egypt, Israel, Gaza Strip, West Bank, Lebanon, Jordan, Syria, Iraq, Kuwait, and Turkey) has long been a central focus for U.S. National Security interests. It is a subtropical region that, like Mexico and the Southwest U.S., is likely to be affected by the expanding Hadley cell.

Figure 46 depicts trends in the prevalence of extreme freshwater deficits and surpluses for the region. The fraction of land area experiencing extreme deficits has increased significantly beginning in the late 1980s. This increase occurred in three escalating cycles, each worse than the previous (1983-1990, 1998-2004, and 2007-2010). The period from 2007-2010 that precedes the onset of the Arab Spring is dominated by persistent widespread freshwater deficits throughout the region. At the same time, the prevalence of extreme surpluses has declined from its peak in the 1950s and 1960s.

The recent amplification of freshwater deficits since the early 1980s is consistent with an expanding Hadley cell. This suggests that more extensive and widespread droughts are likely in a region with chronic water stress and long standing security issues.

Southwest Asia

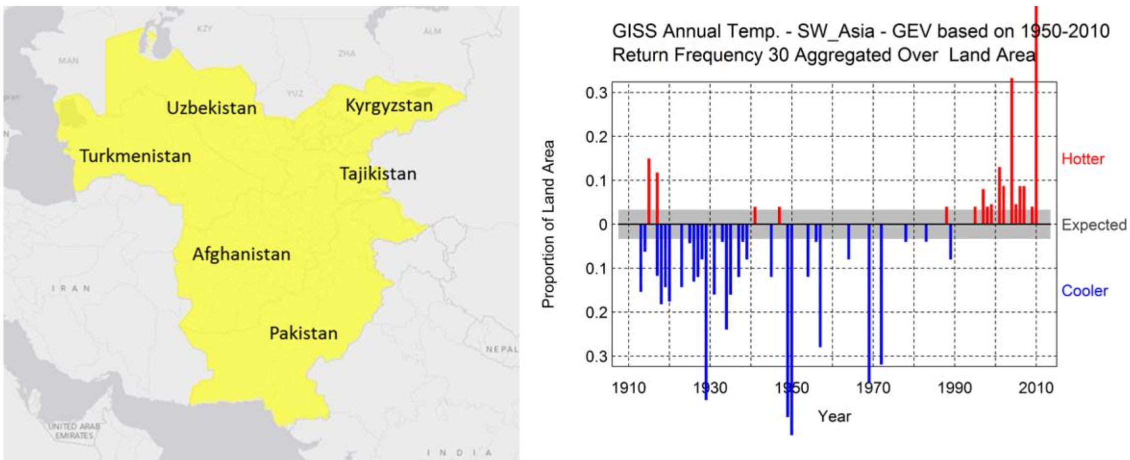


Figure 47. Trends in the Prevalence of Extreme Temperatures for Southwest Asia.

This chart depicts the fraction of land area in the region experiencing extreme annual average temperatures from 1910 to present. The red bars show the fraction of land area experiencing hot anomalies defined as temperatures higher than those one would expect to see only once every 30 years using a 1950-2010 climatology. The blue bars show the fraction of land area experiencing similarly defined cold anomalies. The gray area shows the expected proportions given a stationary and spatiotemporally random climate.

Southwest Asia (Pakistan, Afghanistan, Tajikistan, Kyrgyzstan, Uzbekistan, and Turkmenistan) has been a central focus of U.S. national security interests for the past decade. As with Mexico, the Southwest U.S, and the Eastern Mediterranean, this region is likely to be affected by the expanding Hadley cell.

Figure 47 shows the trend in the prevalence of extreme annual average temperatures throughout the region since 1910. Since 1998, this region has experienced persistent widespread hot anomalies, and cold anomalies have virtually disappeared since the early 1970s. Although relatively widespread hot anomalies are seen in 1914 and 1916, nothing in this 102-year period compares in magnitude or persistence to the recent trends. These trends are consistent with an expanding Hadley cell. Continued expansion of the Hadley cell would imply a hotter, drier regional climate with attendant expansion of desert and arid zones. This would amplify recent diplomatic tensions over the management of transnational waterways in the region.

Indus, Ganges, and Brahmaputra Region

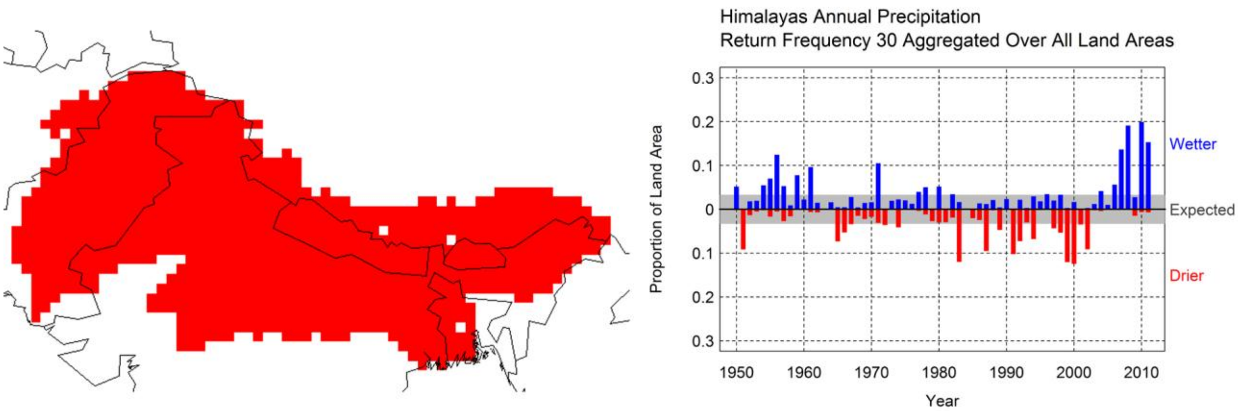


Figure 48. Trends in the Prevalence of Extreme Annual Precipitation in the Indus, Ganges, and Brahmaputra River Basins.

This chart depicts the fraction of land area in the region experiencing extreme total annual precipitation from 1950 to present. The red bars show the fraction of land area experiencing dry anomalies defined as precipitation lower than what one would expect to see once every 30 years using a 1950-2010 climatology. The blue bars show the fraction of land area experiencing similarly defined wet anomalies. The gray area shows the expected proportions given a stationary climate.

Annual precipitation in the Indus, Ganges, and Brahmaputra river basins is dominated by the South Asian monsoon. Figure 48 shows the results of an analysis of annual precipitation extremes restricted to the Indus, Ganges, and Brahmaputra River basins. These results clearly show an increase across the region in the prevalence of annual precipitation extremes over the past six years (2005-2011), consistent with the expected widespread increases in heavy precipitation events with increased warming (SREX). The prevalence of annual extremes during this period is greater than in the earlier period of high annual extremes in the 1950s. As with the analysis of extremes in average annual temperature in Mexico and the U.S./Mexico border region, this analysis cannot rule out the possibility that the recent increase in the occurrence of high annual precipitation amounts may be driven by multi-decadal oscillations such as ENSO and NAO. However, the results are consistent with theory regarding anthropogenic influences on the South Asian monsoon, namely that natural variability will be amplified and a common pattern will be a likely increase in extreme precipitation (SREX). If this trend continues, one would expect to see increased flooding throughout the region, consistent with recent large scale flooding along the Indus, Ganges, and Brahmaputra Rivers.

Since changes in monsoons are related at least in part to changes in sea surface temperatures (SSTs), monsoon forecasts for the Indian subcontinent for either excess or deficit rainfall are likely to be improved by using the links to SST changes in the Indian and Pacific Oceans. Other large-scale variability, such as the NAO or changes in Arctic sea ice, clearly has an influence on the monsoon and is expected to be seen in the record.

China

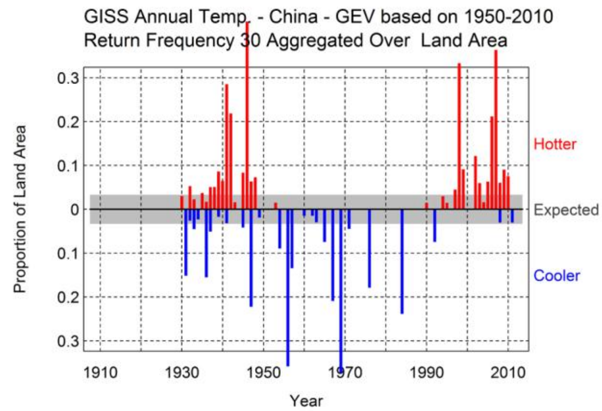


Figure 49. Trends in the Prevalence of Extreme Temperatures for China.

This chart depicts the fraction of land area in the region experiencing extreme annual average temperatures from 1930 to present. The red bars show the fraction of land area experiencing hot anomalies defined as temperatures higher than those one would expect to see only once every 30 years using a 1950-2010 climatology. The blue bars show the fraction of land area experiencing similarly defined cold anomalies. The gray area shows the expected proportions given a stationary climate.

China is now the world's largest emitter of greenhouse gases and SO_2. Its rapidly growing economy has propelled it to become major actor in regional and global affairs. As a large country, China has a complex climatological regime, with different patterns east vs. west and north vs. south. Large portions of China lie in the subtropical regions likely to be affected by an expanding Hadley cell.

Figure 49 shows the trends in prevalence of extreme temperatures for China. In this case there were insufficient data to allow consideration of the period from 1910-1930. Two periods exhibit widespread high temperature anomalies: 1937-1948, and 1998-2010. Both have three very hot years, and cover approximately the same number of years. As is observed in other regions, cold anomalies virtually disappear for most of the later period, while in at least some years in the earlier period low temperature anomalies occurred in greater proportion. The span of years between these two periods – 1950 to 1990 – is dominated by cold temperature anomalies. As with the U.S./Mexico border region, this particular analysis cannot discern whether temperatures in this region are dominated by a) natural variability, b) a warming trend, c) rapid regional industrialization that has resulted in large emissions of aerosols from coal-fired power plants, or d) a combination of all three phenomena.

5.6 References

Abarbanel, H., Koonin, S., Levine, H., MacDonald, G., and Rothaus, O.; Statistics of Extreme Events with Application to Climate, JASON Report JSR-90-405, available at www.fas.org/irp/agency/dod/jason/statistics/pdf.

Allison, I., Bindoff, N. L., Bindschadler, R. A., Cox, P. M., de Noblet, N., England, M. H., Francis, J. E., Gruber, N., Haywood, A. M., Karoly, D. J., Kaser, G., Le Quéré, C., Lenton, T.M., Mann, M. E., McNeil, B. I., Pitman, A. J., Rahmstorf, S., Rignot, E., Schellnhuber, H. J., Schneider, S. H., Sherwood, S. C., Somerville, R. C. J., Steffen, K., Steig, E. J., Visbeck, M., Weaver, A. J.; The Copenhagen Diagnosis, 2009. Updating the World on the Latest Climate Science. The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 60pp.

Archer, C. L.; Caldeira, K., 2008; Historical Trends in the Jet Streams, Geophysical Research Letters 35 (8), DOI: 10.1029/2008GL033614, copyright 2008 American Geophysical Union.

Barriopedro, D., E. M. Fischer, J. Luterbacher, R. M. Trigo, R. García-Herrera, 2011; The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science*, **332**, 220–224.

Battisti, D. S., and Naylor, R., L.; Historical Warnings of Future Food Insecurity with Unprecedented Seasonal Heat, Science, Vol. 323 no. 5911 pp. 240-244, 2009, DOI: 10.1126/science.1164363.

Brasseur, G. P., E. Roeckner, 2005; Impact of Improved Air Quality on the Future Evolution of Climate. Geophys. Res. Lett., 32, L23704, doi:10.1029/2005GL023902.

Brooks, H. E., J. W. Lee, J. P. Craven; The Spatial Distribution of Severe Thunderstorm and Tornado Environments from Global Reanalysis Data, Atmospheric Research 67-68, (2003) 73-94 doi: 10.1016/S0169-8095(03)00045-0.

Cannon, S. H., R. M. Kirkham, and M. Parise, 2001; Wildfire-related Debris-flow Initiation Processes, Storm King Mountain, CO. Geomorphology, 39, 171-188.

Cavazos, T., C. Turrent, D. P. Lettenmaier, 2008; Extreme Precipitation Trends Associated with Tropical Cyclones in the Core of the North American Monsoon. Geophysical Research Letters, 35, L21703, doi:10.1029/2008GL035832.

Church, J., P. L. Woodworth, T. Aarup, W. S. Wilson. 2010; Understanding Sea level Rise and Variability. Wiley Blackwell, ISBN 978-1-4443-3451-7, p. 156.

CSIRO 2012 http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html.

Doster, S., and Ferguson, D.; A Shift Toward Aridity, Southwest Climate Outlook, March 2008, online at http://www.climas.arizona.edu/feature-articles/2008_mar-aridityshift_0.pdf.http://www.climas.arizona.edu/feature-articles/2008_mar-aridityshift_0.pdf.

Emanuel K. A., 2007; "Environmental Factors Affecting tropical Cyclone Power Dissipation." Journal of Climate. 20:5497-5509, DOI: 10.1175/2007JCLI1571.1.

Emanuel, K., 2001; Contribution of Tropical Cyclones to Meridional Heat Transport by the Oceans. Journal of Geophysical Research, 106(D14), 14771-14781.

Evan, A., Kossin, J. P., Chung, C. E., Ramanthan, V., 2011; Arabian Sea Tropical Cyclones Intensified by Emissions of Black Carbon and Other Aerosols. Nature.

Fauria, M. M., Johnson, E. A., 2008; Climate and Wildfires in the North American Boreal Forest. Philosophical Transactions of the Royal Society B 363:2317-2329. doi:10.1098/rstb.2007.2202.

Fink, A. H., U. Ulbrich, H. Engel, 1996; Aspects of the January 1995 Flood in Germany. Weather, 51(2), 34-39.

Francis, J. A., S. J. Vavrus, 2012; Evidence Linking Arctic Amplification to Extreme Weather in Mid-latitudes, Geophys. Res. Lett., 39, L06801, doi:10.1029/2012GL051000.

Frierson, D. M., J. Lu, G. Chen, 2007; Width of the Hadley Cell in Simple and Comprehensive General Circulation Models. Geophys. Res. Ltrs. 34, L18804, doi: 10.1029/2007GL031115.

Gadgil, S. M. Rajeevan, R. Nanjundiah, 2005; Curr. Sci. 88, 1389.

Greene, C. H. and B. C. Monger, 2012; Rip Current: An Arctic Wild Card in the Weather. Oceanography 25(2): 7-9; doi:10.5670/oceanog.2012.58.

Grumm, R. H., 2011; The Central European and Russian Heat Event of July–August 2010. Bull. Am. Met. Soc., 92, 1285-1296.

Hansen, J., Ruedy, R., Sato, M., Lo, K., 2012; "Global Temperature in 2011, Trends, and Prospects", available online at: http://www.columbia.edu/~jeh1/mailings/2012/20120119_Temperature.pdf.

Holland, M. M., C. M. Bitz, B. Tremblay, 2006; Future Abrupt Reductions in the Summer Arctic Sea Ice. Geophysical Research Letters, 33, L23503, doi:10.1029/2006GL028024.

Hong, C. C., H. H. Hsu, N. H. Lin, H. Chiu, 2011; Roles of European Blocking and Tropical-extratropical Interaction in the 2010 Pakistan Flooding, *Geophys. Res. Lett.*, **38**, L13806, doi:10.1029/2011GL047583.

Hudson, R. D., 2011; Measurements of the Movement of the Jet streams at Mid-latitudes. Atmos. Chem. Phys. Discuss. 11, 31067-31090.

IPCC 2007. 4th Assessment. Climate Change, 2007; The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC 2012. SREX; Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Special Report of the IPCC, WMO/UNEP.

Jones, A., D. L. Roberts, M. J. Woodage, and C. E. Johnson, 2001; Indirect Sulphate Aerosol Forcing in a Climate Model with an Interactive Sulphur Cycle. J. Geophys. Res., 106, 20293–20310.

Jones, P. D., D. E. Parker, T. J. Osborn, and K. R. Briffa, 2006; Global and Hemispheric Temperature Anomalies--Land and Marine Instrumental Records. In: Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.

Knutsen, T.; http://www.gfdl.noaa.gov/global-warming-and-hurricanes.

Knutson, T., Landsea, C., Emanuel, K. A., 2010; "Tropical Cyclones and Climate Change: A Review." In Chan JCL, Kepert JD (Eds.), 2010; Global Perspectives on Tropical Cyclones: From Science to Mitigation. World Scientific. ISBN: 978-981-4293-48-8.

Lau, W. K. M. and K. M. Kim, 2011; The 2010 Pakistan Flood and Russian Heat Wave: Teleconnection of Hydrometeorologic Extremes. Journal of Hydrometeorology, doi:10.1175/JHM-D-11-016.1.

Little, J. S., McKenzie, D., Peterson, D. L., Westerling A. L., 2009; Climate and Wildfire Area Burned in Western U.S. Ecoprovinces, 1916-2003." *Ecological Applications* 19(4):1003-1021.

Liu, J., J. A. Curry, H. Wang, M. Song, and R. M. Horton, 2012; Impact of Declining Arctic Sea Ice on Winter Snowfall. Proc. Natl. Acad. Sci. USA Mar 13; 109(11): 4074-9.

Luo, L. and Y. Zhang, 2012; Did We See the 2011 Summer Heat Wave Coming? *Geophys. Res. Lett.*, vol 39, L09708, doi: 10.1029/2012GL051383.

Lutgens and Tarbuck, 2001; The Atmosphere, 8th edition, Prentice Hall. ISBN: 0130879576. ISBN-13: 9780130879578. Figure 7.5.

MacDonald, G., 1992; Persistence in Climate (A JASON report). http://www.fas.org/irp/agency/dod/jason/persistence.pdf.

Mahowald, N., Kloster, S., Engelstaedter, S., Moore, J. K., Mukhopadhyay, S., McConnell, Albani, S., Doney, S., Bhattacharya, A., Curran, M., Flanner, M., Hoffman, F., Lawrence, D., Lindsay, K., Mayewski, P., Neff, J., Rothenberg, D., Thomas, E., Thornton, P., Zender, C., 2010; Observed 20th Century Desert Dust Variability: Impact on Climate and Biogeochemistry. Atmospheric Chemistry and Physics 10, 10875-10893.

Mahowald, N., personal communication, November, 2012.

Mailier, P. J., Stephenson, D. B., Ferro, C. A. T., and Hodges, K. I., 2006; Serial Clustering of Extratropical Cyclones. Monthly Weather Review 134, 2224-2240 (See also Vitolo, R., D. B. Stephenson, I. M. Cook, and K. Mitchell-Wallace, 2009; Serial clustering of intense European storms. Technical Report from Willis Research Network, available at http://www.willisresearchnetwork.com/Lists/Publications/Attachments/43/WRN_European_Windstorm_Clustering_Paper.pdf).

Marlon, J. R., Bartlein, J. P., Walsh, M. K., Harrison, S. P., Brown, K. J., Edwards, M. E., Higuera, P. E., Power, M. J., Anderson, R. S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F. S., Lavoie, M., Long, C., Minckley, T., Richard, P. J. H., Scott, A. C., Shafer, D. S., Tinner, W., Umbanhowar, C. E. Jr., Whitlock, C., 2009; Wildfire Responses to Abrupt Climate Change in North America." *Proceedings of the National Academy of Sciences* 106(8):2519-2524.

Maue, R. N., 2009; Northern Hemisphere Tropical Cyclone Activity. Geophysical Research Letters, 36, L05805.

Meehl et al., 2009; Relative Increase of Record High Maximum Temperatures Compared to Record Low Minimum Temperatures in the U.S. Geophys. Res. Ltrs. 36, L23701, 5 PP., 2009
doi:10.1029/2009GL040736.

Meehl, G. A., Arblaster, I. M., Collins, W. D., 2008; Effects of Black Carbon Aerosols on the Indian Monsoon. Journal of Climate 21(12), 2869-2882.

Meehl, G. A. and co-authors, 2009; Decadal prediction: Can it be skillful? *Bull. Amer. Meteorol. Soc.*, 90, 1467—1485.

Meyssignac, B., D. Salas y Melia, Becker, M., Llovel, W., Cazenave, A., 2012; Tropical Pacific Spatial Trend Patterns in Observed Sea Level: Internal Variability and/or Anthropogenic Signature? Climate of the Past 9: issue 2.

Moon, T., Joughin, I., Smith, B., Howat, I., 2012; 21st-Century Evolution of Greenland Outlet Glacier Velocities. Science 336: No. 6081 pp.

Naik, N., Online at http://www.ldeo.columbia.edu/res/div/ocp/drought/science.shtml.

National Snow and Ice Data Center, Arctic Sea Ice News and Analysis, online at http://nsidc.org/arcticseaicenews/.

Nerem, R. S., Chambers, D., Choe, C., and Mitchum, G. T.; Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions. *Marine Geodesy* 33, no. 1 supp 1 (2010): 435.

NOAA NCDC: http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html.

Ostermeier, G. M., Wallace, J. M., 2003; Trends in the North Atlantic Oscillation-Northern Hemisphere Annular Mode During the Twentieth Century. J. Climate 16, 336-341.

Palmer, T., Hagedorn, R., 2006; Predictability of Weather and Climate. Cambridge University Press, ISBN: 0-521-84882-2.

Peterson, T. C., P. A. Stott, and S. Herring, 2012; Explaining Extreme Events of 2011 from a Climate Perspective. Bull. Am. Met. Soc. 1041-1067. doi: http://dx.dri.org/10.1175/BAMS-D-12-00021.1.

Prabhu, A., P. N. Mahajan, and R. M. Khaladkar, 2011; Association of the Indian Summer Monsoon Rainfall Variability with the Geophysical Parameters over the Arctic Region. Int. J. Climatology. doi: 10.1002/joc.2418.

Prospero, J. M., and P. J. Lamb, 2003; African Droughts and Dust Transport to the Caribbean: Climate Change Implications. Science, 302, 1024–1027.

Roy, Shouraseni Sen, 2011; The Role of the North Atlantic Oscillation in Shaping Regional-Scale Peak Seasonal Precipitation across the Indian Subcontinent. Earth Interact., 15, 1–13, doi: http://dx.doi.org/10.1175/2010EI339.1.

Sallenger, A. H., K. S. Doran, P. A. Howd, 2012; Hotspot of Accelerated Sea Level Rise on the Atlantic Coast of North America. Nature Climate Change doi:10.1038/nclimate1597.

Sarachik, E. S. and M. Cane, 2010; The El Niño-Southern Oscillation Phenomenon. Cambridge University Press.

Seidel, D. J., & Randel, W. J., 2007; Recent Widening of the Tropical Belt: Evidence from Tropopause Observations. Journal of Geophysical Research, 112, D20113.

Seidel, D. J., Fu, Q., Randel, W. J., Reichler, T. J., 2008; Widening of the Tropical Belt in a Changing Climate. Nature Geoscience, 1, 21-24.

Seneviratne, S. I., D. Lüthi, M. Litschi, C. Schär, 2006; Land-atmosphere Coupling and Climate Change in Europe. Nature, 443, 205-209.

Serreze M. C., and Barry, R. G., 2011; Processes and Impacts of Arctic Amplification: A Research Synthesis, Global and Planetary Change 77 85–96.

Shuka, J., 2007; 2007 Monsoon Mysteries. Science 318, 204-205 doi: 10.1126/science.1150045.

Slocum, M. G., Beckage, B., Platt, W. J., Orzell, S. L., Taylor, W., 2010; Effect of Climate on Wildfire Wize: a Cross-scale Analysis. *Ecosystems* 13:828-840. DOI: 10.1007/s10021-010-9357-y.

Sperna Weiland, F. C., van Beek, L. P. H., Kwadijk, J. C. J., Bierkens, M. F. P.; Global Patterns of Change in Discharge Regimes for 2100, Hydrol. Earth Syst. Sci. Discuss., 8, 10973–11014, 2011, doi:10.5194/hessd-8-10973-2011.

Stroeve, J. et al., 2007; Arctic Sea Ice Decline: Faster than Forecast. Geophysical Research Letters 34, L09501.

Trenberth, K. E., J. T. Fasullo, 2012; Climate Extremes and Climate Change: The Russian Heat Wave and Other Climate Extremes of 2010. J. Geophys. Res., doi: 10.1029/2012JD018020, in press. Available at http://www.cgd.ucar.edu/cas/Trenberth/trenberth.papers/JGR2012JD018020-ClimateExt.pdf.

Trewin, B., 2012; A Daily Homogenized Temperature Data Set for Australia. International Journal of Climatology, Article first published online: 13 Jun 2012; doi: 10.1002/joc.3530.

UCAR COMET Program; http://www.meted.ucar.edu/norlat/sat_features/blocking_patterns/overview.htm).

Ulbrich, U., A.H. Fink, M. Klawa, and J. G. Pinto, 2001; Three Extreme Storms Over Europe in December 1999. Weather, 56, 70-80.

University of Colorado, 2012; map from http://sealevel.colorado.edu/content/map-sea level-trends Nerem, R. S., D. Chambers, C. Choe, G. T. Mitchum; Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions. Marine Geodesy 33, no. 1 supp 1 (2010): 435).

University of Wisconsin Space Science and Engineering Center; SSEC Data Center; http://www.ssec.wisc.edu/datacenter/.

Vecchi, G. A., T. R. Knutson, 2008; On Estimates of Historical North Atlantic Tropical Cyclone Activity. Journal of Climate, 21(14), 3580-3600.

Wallace, J. M. and P. Hobbs, 2006; Atmospheric Science, 2nd Edition, Elsevier/Academic Press. ISBN: 9780 127329512.

Walton, G., 2012; http://www.weather.com/blog/weather/ 10 June 2012.

Westerling, A. L., Swetnam, T. W.; Interannual to Decadal Drought and Wildfire in the Western United States. Eos, Vol. 84, No. 49, 9 December 2003.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., Swetnam, T. W., 2006; Warming and earlier Spring Increase Western U.S. Forest Activity." *Science* 313:940-943 (August).

Yuan, X., E. F. Wood, L. Luo, M. Pan, 2011; A First Look at Climate Forecast System Version 2 (CFSv2) for Hydrological Seasonal Prediction. Geophys. Res. Letters 38 1-7.

6 Recommendations

As a result of this examination of national security needs in the context of our ability to predict changes in weather and climate extremes, in our judgment there must be new commitments for a national strategy for strategic observations and for the way those observations address the testing and improvement of forecasts.

This section summarizes the recommendations for observations to improve forecasts of weather and climate extremes and their impacts. It addresses the global record; polar, land, and ocean observations; storms and rainfall; improvement of weather predictions; and human impacts. It concludes by identifying needs for improving models for better predictions on a regional level. We recognize that the world science community has been engaged in developing criteria and essential variables for monitoring weather and climate, and these recommendations build on those. Unfortunately, because of budget constraints around the world, the basic Earth observing capability – satellite remote sensing and in situ measurements – is declining. The national security implications of continued and accelerated extreme weather are serious and warrant consideration of support for improved observations and models.

The focus of this report is on near-term weather and climate extremes; how they are driven and how they might be expected to develop in the future, with an eye to the particular needs of national security. With that focus in mind, we have developed a series of specific recommendations that, if followed, could help dramatically in improving both our understanding and predictability of near-term climate extremes. We acknowledge the contribution thus far of the Intelligence Community through the Global Fiducial Program (which is providing access to declassified national imagery for scientific use) the DoD (particularly the Navy), and others. We request that they all continue to evaluate the utility and contribution of existing systems and sustain activities that are underway.

Recognizing the interest and need for regional forecasts, we have also identified some areas where additional data collection could have a significant impact on regional forecasts. This section is divided into seven parts: the global record, polar observations, ocean observations, land observations, storms and rainfall, weather observations, and human impacts. Finally, we note that the information and findings in this report draw heavily on the extensive global data sets for temperature, pressure, humidity, rainfall, snow and ice, and a host of other essential variables required for monitoring and understanding weather and climate for warnings and forecasts. This information has been identified through an ongoing series of reports sponsored by the various responsible international agencies, including:

- The World Meteorological Organization
- The Intergovernmental Oceanographic Commission
- Several national institutions, including the U.S. NOAA, NSF, NASA, EPA, and others both in the U.S. and abroad.

Improved understanding of both short- and long-term weather and climate phenomena are critically dependent on the continuation of such data collection. Unfortunately, because of budget constraints around the world, the basic earth observing capability – satellite remote sensing and in situ measurements – is declining. As a consequence we are losing data just at a time when it is of most importance. Since the data not gathered today are lost forever, we add our voice to those advocating continuation of the basic Earth observing system.

In summary: *As a result of this examination of national security needs in the context of our ability to predict changes in weather and climate extremes, in our judgment there must be new commitments for a national strategy for strategic observations and for the way those observations address the testing and improvement of forecasts.*

6.1 The Global Record

On a global scale, the primary science need is an accurate and continuous determination of the global energy balance: the net energy over the full bandwidth of radiation in and out. This information allows us to determine the relative strength of drivers (greenhouse gases and aerosols) of the climate. With this information, the impact of changing drivers, such as reduction of aerosols, can be directly determined, and it is possible that regional effects may be observed, an important security issue. The measurements required include direct observations of the energy input from the sun, the reflected energy through total and disaggregated albedo, and emissions over the full bandwidth.

The second global priority for measurements is a focus on industrial aerosols. There remain uncertainties in understanding of the radiative interactions of aerosols with their environment, and in measurements of the concentration of the different kinds of aerosols in the atmosphere. Monitoring emissions by ships at sea is particularly important, since the fuel used is sulfur-rich. Since a rapid rise or decrease in these short-lived aerosols could lead to either rapid cooling or rapid warming, it is critical from a security standpoint to understand as much as possible the magnitude of such impacts. The measurements required include a focus on aerosol emissions and concentrations, particularly over oceans and major shipping routes, accompanied by research on the radiative properties of aerosols.

6.2 Polar Observations

As has been noted, processes and changes in the polar regions are key to understanding many aspects of near-term climate change. Moreover, rapid changes in the Arctic directly affect Navy and Coast Guard operations, yet we have no systematic surveillance operation in place capable of quantitatively observing ice volume the flow of heat into the remaining ice systems, and changes in oceanic and atmospheric flow patterns. This prevents the development of a reliable forecast of when all permanent floating ice will be gone from the Arctic Ocean.

In particular, global sea level rise is highly sensitive to changes in mass balances of the ice caps over Greenland and Antarctica. The science need is to know how much ice is in the cap and how fast it is changing, and where and how fast it will melt with increased temperatures. We need to reduce the uncertainties in our knowledge of spatial and temporal changes in the masses of these ice caps. At present there is no systematic approach in place for mapping the dynamics of the ice structures of Greenland that are now exposed to increasing heat flow from both the ocean and atmospheric component and which in turn control the increase in sea level from the disintegration of the Greenland glacial structures. This is true also for Antarctica: there is no observing system capable of quantitatively tracking heat transport into the base regions of the West Antarctic ice sheet. Without such knowledge, projections of that ecosystem's stability are impossible to determine. Key needs are accurate measurements of the actual shape of the ice caps, at their top and bottom. Additional information can be obtained with gravity measuring drones, and the shape of the top of the ice sheet can be observed with altimeters and synthetic aperture radar. Techniques for determining the shape of the bottom of the ice sheets also need to be developed and deployed.

We also need a better understanding of the sea ice cover in the Arctic – how its area and thickness is changing – so that the total mass change over time can be documented. Of particular importance are processes at the ocean-sea ice edge where warmer water impinges on colder ice: melting at the bottom of the sea ice, air-sea heat transfer at the surface, and transfer of heat downwards into the ocean. Use of satellite imagery, drifters with in situ technology for monitoring temperature, salinity, and ocean currents near and below the ice, and bottom-mounted upwards-looking instruments will be required.

A second high priority for the Arctic is monitoring the change in the region of permafrost. Much of the infrastructure in the Arctic is built on permafrost. The current warming is already leading to sinking structures, and continued melting will require serious adaptation. From a science standpoint, it is crucial to understand how permafrost has been changing in response to recent Arctic warming, and how fast and where it will change with predicted increases in warming. Since buried oil pipelines and other energy and port infrastructure depend critically on the continuing presence of permafrost, any information about how fast the permafrost will melt is important for security concerns. To monitor and understand these changes, drill holes and other in situ instrumentation is required, and there may be opportunities for application of space techniques. In addition, better models of permafrost/warming interactions are required. Associated with the melting of the permafrost is the emission of methane, a potent and abundant greenhouse gas. There is no observing system to quantitatively track the flux of carbon isotopes from either the terrestrial or ocean components of the clathrates and permafrost in the developing melt zones in the Arctic basin. Methane should be monitored continuously in the permafrost region. Finally, there is no systematic way of mapping increased temperatures that penetrate the continental shelf of the Arctic Ocean and result in gas flux emitted from hydrates that affect low frequency sound propagation and, through phytoplankton production, the optical properties of coastal waters that are important for the Navy.

6.3 Ocean Observations

Section 3 has outlined the critical role of the ocean in heat storage and transport, and noted that observations are still inadequate to calibrate the general circulation models. There is in place an extensive program of global ocean monitoring with Argo floats that provide temperature information to a depth of 2,000 meters, but coverage of the deep ocean remains sparse. In order to understand fully how the climate system responds to a radiative energy imbalance, we must know where and how fast the ocean can store excess heat. At this point our knowledge is limited because of the lack of observations. This is a critical lack, because it impedes our knowledge of how the climate is changing and will change with greenhouse gas/aerosol forcing. The required observations include comprehensive measurements of temperature in the ocean below 2,000 meters and at higher latitudes, areas not covered by Argo. Augmenting the Argo float array should contemplate moorings that provide deep measurements (expansion of the OceanSites program) and spatial averaging with acoustic tomography, which has been shown to be sufficiently accurate to monitor the expected changes in heat storage. The tomography program now in the Arctic should be expanded to cover more extensive regions of the deep ocean.

A second ocean priority should be to focus on more comprehensive measurements of the processes related to the El Niño/Southern (ENSO) oscillation in the ocean and atmosphere as it goes through its various phases in different parts of the world. As noted in Section 4, near-term climate extremes are heavily modified by on-going ENSO processes, and much of the predictability in the near term is associated with ENSO. Thus the better we can monitor ENSO and its global evolution, the better we will do on near-term prediction of ENSO impacts. Since the ENSO phenomenon extends around the globe, more expansive measurements are required, including measurements in the Indian and Atlantic Oceans. Specific measurements required include extension to the Indian and Atlantic Ocean of the existing arrays that monitor surface winds, ocean currents, and sea surface and deeper temperatures in the tropical Pacific Ocean. Satellite and in situ measurement of surface winds are a key element of the input to forecast models.

6.4 Land Observations

Changes in land cover can drive climate change, even over the short run. For example, we note in Sections 2 and 4 the prediction of expansion of the Hadley cell circulation with poleward movement of areas of droughts, but some countries have found that with proper use of land it is possible to reduce the impact of such droughts. In any case, to understand how regional climate will change, it is essential to know the surface boundary conditions, and human changes in land cover are an important part of that process. The fact is that many aspects of long-term or even permanent changes in climate, and hence extreme weather, are tied to human changes in land cover: agriculture, deforestation, fires, roads, and development. Measurement requirements include monitoring of regional changes in albedo or evapotranspiration that might be associated with human changes, monitoring biogeochemical processes, and detailed high resolution mapping of changing landscapes.

Water is a key need for countries, driving economic decisions and infrastructure development. Water availability can affect infrastructure siting, agricultural planning, and new development. It is essential that we monitor the magnitude and location of droughts, floods, and highs and lows of river flows. Monitoring of water on the land surface requires the use of satellites and in situ instruments for information on surface water, soil moisture, and snowpack, since the amount of snow is directly related to spring water flows. Altimeters can be usefully applied for lake level monitoring. A good example of what is needed is an observing system that tracks changes in the glacial structure of the Tibetan plateau that controls the water supplies to China and to India.

6.5 Storms and Rainfall

In Section 2 we noted that the current best estimate is for fewer but stronger tropical cyclones, particularly over the North Atlantic Ocean. These studies were based on North Atlantic information because there is a lack of information on historical North Pacific cyclone intensity. With the reduction of aircraft flights through Pacific storms starting in 1980, our information base has been limited. In order to provide better forecasts of what will happen, and where the storm tracks might go, we need a long-term record of intensity as well as location. The location and track of major storms is critical for forecasting impacts of many kinds, and any improvement in forecasting is welcome. The measurements required include in situ monitoring of winds and precipitation. This can be done be manned aircraft, but there may be good ways to do this with UAVs as well as with existing satellite sensors.

We lack adequate information on precipitation both globally and regionally. Although there were detailed satellite measurements of tropical rainfall with the TRMM mission, at present we have only sparse coverage of global precipitation; NASA has a Global Precipitation Mission (GPM) planned for launch in 2014. Such measurements will help us forecast rainfall and hence, for example, agricultural productivity in tropical countries that will be of security interest. Required measurements include the kind of measurements proposed by the NASA GPM mission augmented by more regional information that can come from improvement of in-situ networks for measurements of water content and hail. Supplementary information also of importance includes dust storms and lightning.

6.6 Weather Observations and Forecasts

Improvement of near-term weather forecasts requires both a continued record of weather and climate conditions around the globe and the improvement of modeling, particularly for forecasts on the regional scale. In terms of the global record of weather, the conclusions of this report have been significantly informed by analyses leveraging NOAA/CPC Global land surface air temperature and precipitation data. Further analysis on this topic requires a continued NOAA data set, emphasizing the importance of the continuation of global temperature and precipitation measurements along the lines discussed above.

From a modeling standpoint, there is evidence that downscaling the existing global models has not yet been a reliable way to provide forecasts on regional scales. Therefore, in addition to further work on downscaling, complementary studies on merging regional data and understanding from teleconnections and processes like ENSO will be necessary to provide more reliable regional forecasts. Development of reliable high-resolution global models will also require more research on parameterizations, higher speed computers and new computational techniques for higher spatial and temporal resolution weather forecasting. All of this will have to be done in the context of better computing infrastructure and associated funding for adequate support personnel.

6.7 Human Impacts

The report has also noted that human-induced changes can affect near-term climate. We have mentioned land-use change above as one key aspect. Two other changes of importance to weather and climate are the spread of cities as urban heat islands and emitters of aerosols and greenhouse gases, and the possibility of wide-spread human interventions or geo-engineering. The spread of cities and of human habitation in general can be monitored with measurements of lights at night. Population migration, economic development, and even the impact of major disasters can also be related to this parameter. Up to now, these measurements have been made by the Defense Meteorological Satellite Program (DMSP). We endorse the continuation of the DMSP program with improved night light capability that is a joint Navy/Air Force mission.

In terms of geo-engineering, the interventions include weather modification, adding sulfates into the stratosphere, injection of water into the tropical troposphere, and other schemes that have been proposed. There have been many weather modification activities carried out on sub-national scales in recent years, but no large-scale activity has yet been planned or funded. However, with impacts of global warming becoming more evident around the world, it is likely that some country or groups of countries may decide unilaterally to move beyond simple local weather modification to deploy some large-scale system. Little is known about how any of the large-scale geo-engineering projects will affect the climate. There are most likely to be both primary and secondary effects that cannot be predicted.

To the extent that the human intervention begins to affect climate and weather in new and unpredictable ways on a trans-national scale, this is a security issue. It is likely that the next stage of geo-engineering will be tests to determine whether systems should be ramped up to national or continental scale. Given the potential and unknown global impact, the test phase should be closely monitored. There should be careful collection of information on what kinds of geo-engineering projects are contemplated and where they would be deployed. Once such projects are in place, there will need to be both global and regional monitoring of effects and impacts.

7 Climate Extremes: Principal Findings and Conclusions

KEY JUDGMENTS

Increasing Weather Extremes. There has been a significant increase in weather extremes over the last decade. Droughts, storms, tornadoes, the attendant floods and wildfires, highly-variable weather around the world, and other extremes are affecting society globally. All of this is consistent with a warmer and wetter atmosphere driven by radiative imbalance from greenhouse gas warming. Although the temperature changes due to greenhouse warming will be relatively small in the coming decade, the positive shift of mean temperature will magnify the extremes to a point where they are beyond what has been seen before. The analysis finds that, absent unknown or unpredictable natural forces, *the upswing of extreme events observed in the past decade is likely to continue in the near term as warming and natural variability will combine to produce changing weather conditions around the world*. We can no longer assume that the extremes of tomorrow will resemble the extremes of yesterday.

The National Security Interest. *Climate-induced stress will affect water and food availability, energy security, and the stability of critical infrastructure,* use of the global common such as the Oceans and the Arctic region, and critical ecosystems resources. These are U.S. national security interests that have been, and will continue to be, affected by climate and weather extremes patterns. Humanitarian, economic, and political interests are all affected as nations attempt to deal with the potential impacts of changing extremes.

Maintaining Vigilance. *We render the judgment that the harsh influences of climate extremes necessitate their careful consideration in threat analysis, mitigation, and response.* It is in the best interest of the U.S. to maintain vigilance regarding climate and weather extremes, the behavior of nations in their attempts to mitigate or adapt to the effects of changing extremes, and impacts on social, economic, and political well-being.

Observed change in the climate system has garnered the attention of many worldwide and has become an issue of ongoing concern for the US. In 2008, then-National Intelligence Council Chairman Thomas Fingar stated to Congress that, "… we judge that global climate change will have wide-ranging implications for U.S. national security interests over the next 20 years, because it will aggravate existing problems — such as poverty, social tensions, environmental degradation, ineffectual leadership, and weak political institutions." The recent worldwide prevalence of extreme weather - anomalous droughts, floods, severe storms, and heat waves - raises the specter of significant impacts of changing climate in the near term. Because of the potential proximate threat to U.S. security interests, this report's authors consider what one could expect over the next decade – would these extreme conditions persist? Are the extreme weather conditions a result of greenhouse warming? What are plausible impacts on U.S. national security interests?

In developing the conclusions and recommendations for regional predictions, the authors have focused on insights derived from statistical analysis, physical understanding, and basic energy balance models, recognizing the ability of general circulation models to forecast changes and interpret the physics on a global scale but also their limitations for high-resolution or near-term forecasts. The study relied also on analysis of historical temperature and precipitation data, together with a review of the latest literature on climate change, weather extremes, and links to climate drivers. The goal is to outline present understanding of expectations for extreme events in the near term to ascertain societal consequences and plausible national security implications.

As a result of an examination of recent weather and climate extremes the study finds:

1. ***Increases in atmospheric energy from increasing concentration of greenhouse gases and a reduction of aerosols are leading to increased warming globally, enhanced in the Arctic.*** Discussions of warming in the past have focused on global average warming, but from a national security perspective, extremes are the key. Land temperatures are warming faster than the ocean surface. The data show that an underlying global temperature trend has been accompanied by significant increases in the number of record high high-temperatures and record high low- temperatures on daily, monthly, and annual time scales, as well as in longer sequences of hotter nights. Reductions in snow cover and soil moisture can intensify heat waves. At its current accelerated rate of decrease, the Arctic could be ice-free year during the summer within a few decades, completely changing the energy balance of that region and leading likely to global changes. Contraction of snow cover area and increases in thaw depth of permafrost are all expected, as is continued melting of the large ice sheets of Greenland and Antarctica. The ocean is observed to be warming, primarily in the upper layers, but data for the deeper oceans are sparse.
2. ***The actual observed changes in the atmosphere will reflect a combination of greenhouse gas warming together with natural variability.*** Increasing evidence is pointing to the fact that changes in Earth's energy balance are driving a warmer and wetter atmosphere with interactions between climate change and natural variability. In any given year, the natural variability may dominate, but the potential significance of the interplay between natural variability and human-induced changes in regulating at least the short-term expression of the global climate system is not well understood. For example, the observed warming in certain regions from El Niño itself leads to more extreme events, which could be enhanced by trends in global warming.
3. ***Aerosols play a stronger role in modifying short-term radiative balance than previously thought.*** Up to now, the near-term impact of greenhouse gas warming has been significantly reduced by the negative forcing from aerosols. Now, with many countries (e.g., U.S., E.U., and China) reducing aerosols for air quality and health reasons, and attention being paid to reducing emissions from ships burning high-sulfur bunker fuel, the negative forcing due to aerosols is likely to be reduced and warming is likely to increase. As a consequence, we expect trends in climate and climate extremes not just to persist, but to accelerate and to lead to increasingly anomalous weather patterns.
4. ***A warming ocean reflects the fact that Earth is absorbing more energy from the sun than it is emitting back to space.*** Greenhouse gas concentrations are steadily increasing, leading to a planetary energy imbalance. The energy excess is reflected primarily through a change in the heat content of the ocean, and in fact, recent studies demonstrate a persistent, long-term increase of the average bulk temperature of the ocean. This positive

radiative forcing trend is providing a context for rapid changes in weather and climate extremes, forcing changes on the Earth's surface, particularly on the cryosphere. The heating of the ocean is currently the best direct observational evidence that the Earth is currently out of energy balance, that it is absorbing more energy from the sun than it is emitting to space.

5. ***The abundance of water vapor in the atmosphere has increased and will continue to do so.*** A warmer atmosphere is capable of holding more water. When conditions favor precipitation, it is probable that the intensity of the resulting rain or snowfall will increase, reflecting the enhanced supply of water vapor. We also see greater frequencies of large precipitation events. We expect weather patterns that will be generally more extreme (and different from the past), as defined by increased incidences of floods in some regions compensated by droughts in others. This is the pattern that has been observed over the recent past, and the trend is likely to persist and become even more severe in the future.

6. ***Large-scale circulation patterns throughout the northern hemisphere will be increasingly affected by Arctic warming.*** It appears that Arctic amplification, the decrease in the overall gradient of temperature between mid and high latitudes, is consistent with a decline in the strength of the polar jet. A possible consequence could be larger north-south meanders in the jet as it progresses slowly zonally around the planet, leading to more variable weather patterns, including more severe winter outbreaks in the U.S. and Europe in the future.

7. ***Changes observed in atmospheric circulation include the poleward expansion of the tropical Hadley cell.*** There is observational evidence for expansion of the Hadley cell by as much as two degrees of latitude between 1979 and 2005. The major desert regions of the world are generally co-located with the descending branches of the Hadley circulation system. A poleward expansion of these descending branches of the Hadley cell is expected with greenhouse warming, but the observed expansion is actually greater than predicted by models. In any case, the expansion is likely to continue to cause arid regions to extend to higher latitudes: think of the Sahara Desert extending across the Mediterranean into southern Europe or the southwestern desert of the U.S. moving north into the grain-producing region of the country.

8. ***Observations from the past century show recent increases in weather and climate extremes globally.*** A recent trend towards more extremes in weather and climate is clear in the records of the past century. For example, relatively few locations experienced 20 or 30-year high temperature anomalies in the 1950s, whereas the vast majority of the land surface experienced 30-year high temperatures at least once in the period 2002-2011. These highs are occurring around the world – not only in boreal and Arctic regions where average temperatures have increased the most, but also in agricultural croplands and populated areas. The ratio of record highs to record lows is accelerating. Wildfires appear to be increasing in intensity. This trend is expected to continue and thus to have an increasing impact on society.

9. ***With increased warming, tropical cyclones are expected to get stronger, continuing the observed trend in the North Atlantic, and mid-latitude storm tracks in the Northern Hemisphere are expected to move north.*** There is good evidence that precipitation intensity will increase, thus making impacts from a given storm more severe. Precipitation intensity is projected to increase almost everywhere on the planet, but increases of "dry days" (number of days between storms) is projected to increase over many extratropical areas.

10. ***The prognosis for the next decade points to the likelihood of continued and intensified weather and climate extremes.*** Continued human-induced forcing of Earth's energy balance will affect the energetic state of the atmosphere and ocean, and perturb atmospheric circulation mechanisms in ways that are likely to enhance extreme conditions. Although the changes due to greenhouse warming will be relatively small globally, the shift of mean temperature magnifies the extremes to a point where they are well beyond what has been seen before. While it is still not possible to predict where they will occur, they will be more prevalent. Only rapid reduction in radiative forcing would reduce the likelihood of a future increase in prevalent extremes.

11. ***Sea level rise is accelerating.*** Observations show that sea level is going up at least twice as fast as projected by the latest IPCC assessment. The rise will be felt differentially around the world. Detailed predictions are hampered by a lack of knowledge of the processes that could contribute to acceleration in the melting of the ice sheets on Greenland and Antarctica. To determine the near-term impacts, more accurate measurements of the changing shape of the ice sheets and the melting processes are urgently required.

12. ***Regional effects of near-term climate stress will be felt across the globe.*** Regional trends are driven by large-scale features of the climate system such as the ocean sea surface temperatures, the atmosphere's water vapor holding capacity, and atmospheric circulation patterns. We can expect increased warming worldwide with amplification in the Arctic, a warmer ocean, more intense storm events in the tropical regions, generally drier subtropical regions, and likely wetter conditions in temperate and boreal regions but characterized by more intense and less frequent precipitation events. The effects are worldwide and impact all nations.

13. ***Improving predictability will require better understanding of the climate system and how it responds to global warming.*** While considerable skill already exists for predicting some near-term variability, such as the evolution of El Niño-Southern Oscillation, there is less skill in projecting the changes associated with other sources of natural variability, such as the North Atlantic Oscillation. Improved understanding of the combination of human-induced climate change together with these sources of natural variability will lead to better local and regional predictability of extreme weather. There is persistence in blocking patterns that can be exploited for short-term predictability, but blocking is poorly simulated in models and the impact of radiative forcing on blocking is not well understood.

14. ***Continued and enhanced observations, particularly in the polar regions, are critical for improving regional predictability.*** Predictability requires both better models and better data. Global data are essential not only to monitor changing patterns of weather and climate, but also to provide information that scientists can use to study and improve understanding of processes in the climate system to enhance the capability of models to predict climate change. We still lack adequate understanding and require assurance of adequate long-term monitoring of the global radiative balance from the top of the atmosphere, so that we can understand the effect of various drivers. The heat content of the ocean provides a next-best proxy. Deep measurements in the ocean and data from higher latitudes, particularly in seasonally ice-covered regions, are needed to close the heat budget. Regional data, particularly from the ocean near outlet glaciers and on the state of the Greenland and West Antarctic ice sheets, are essential if we are to monitor and understand possible ice sheet disintegration in order to inform predictions of possible rapid sea level change. All of these observations over a long period will be required to initialize and evaluate the models of the future.

15. ***Impacts will be felt on water, food and energy security, and critical infrastructure – each in the U.S. National Security Interest.*** Human security and the interests of most nations are at stake as a result of environmental changes we expect to see in the coming decades. It appears that the impacts of climate changes are more imminent than previously thought. This is cause for significant concern in the latter part of this century, but will affect society in significant ways today and through the coming decade. The impact upon human security and the individual, and the collective response of nations will be profound. The national security context will change. U.S. national security interests have been, and will continue to be, affected by extreme weather patterns. Humanitarian, economic, and political interests are all affected as nations attempt to deal with the potential impacts of changing weather extremes. It is in best interest of the U.S. to maintain vigilance regarding extreme weather patterns, the behavior of nations in their attempts to mitigate or adapt to the effects of changing extremes, and impacts on social, economic, and political well-being.

CLIMATE EXTREMES AND NATIONAL SECURITY – THE BOTTOM LINE

Climate change has entered the mainstream as a potential threat to U.S. national security. The 2010 Quadrennial Defense Review and the 2010 National Security Strategy identify climate change as likely to trigger outcomes that will threaten U.S. security. These assessments have had to rely on projections of climate change tuned to identify impacts over roughly a one-century time frame. This time frame is driven by the nature of the questions that dominated the initial literature (e.g., what impacts can be expected from a doubling of pre-industrial carbon dioxide) and the fact that global climate models are generally able to resolve expected impacts only over large scales and the long term.

Having arrived at a condition where climate change has been identified as a likely threat to U.S. national security interests, but with little ability to clarify the nature of expected climate impacts over a timeframe that is relevant to security decision-makers, the authors focused on the near-term impacts from climate change (over the next decade). In short, the analysis finds that, absent unknown or unpredictable forces, the increase in extreme events observed in the past decade is likely to continue in the near term as accelerated warming and natural variability combine to produce changing weather conditions around the world. This will impact Water Security, Energy Security, Food Security, and Critical Infrastructure, and brings into focus the need to consider the accelerating nature of climate stress, in concert with the more traditional political, economic, and social indicators that inform our analyses.

Epilogue

THE EXTREME WEATHER CONTINUES …

Extreme weather conditions and impacts continue to dominate recent news headlines. Here are a few of the recent examples (as of October 2012):

- **Colorado Wildfires:** Colorado has been hit with a series of wildfires, the worst since the drought-stricken year of 2002. The High Park Fire, west of Fort Collins, has consumed 83,205 acres. (International Business Times, 2012)
- **Midwest Corn Belt Heat and Lack of Rain:** Corn is facing the worst crop conditions in two decades. Unusual heat and lack of rain threaten this year's crop yield and has put a fire under futures prices. There had been expectations of a bumper crop, needed to replenish U.S. stocks. Last year's corn stocks were just 850 million bushels, the lowest level since 1995. (CNBC, 2012)
- **Weak start to the Indian Monsoon:** The worst start to the monsoon season in India in three years is threatening crops from rice to sugar cane, stoking concern that the nation may limit exports to preserve supplies. Soybean futures in India climbed to the highest level since 2003 and corn rose to a five-month high. Rainfall from June 1st on is estimated at 23% below average. (Bloomberg, 2012)
- **Flooding in Assam, India:** Assam's rainfall at the start of the monsoon has been 31% greater than normal. Large swathes of three 'food bowls' in the province are under water. A government spokesperson indicated the flood is the biggest since 1998. (Hindustan Times, 2012)
- **Tropical Storm Flooding in Florida:** Tropical Storm Debby stalled for 2 days in the Gulf and dumped two feet of rain on areas of Florida. The Anclote River rose more than 27 feet, well above major flood level, and may remain above flood level for a week. (Reuters, 2012)
- **China Flooding:** Torrential rain since June 20 across central and southeastern China has affected more than 10.4 million people. Crops in 738,000 hectares were lost in the deluge, resulting in direct economic losses worth $1.62 billion. (RTT News, 2012)
- **Russia Wildfires:** Russia has declared a state of emergency in several eastern regions due to hundreds of wildfires. Fires raged for months during the summer, destroying thousands of hectares – more area than the deadly fires of 2010. (Earth Snapshot, 2012, NASA, 2012)
- **Loss of Arctic Sea Ice:** Sea ice in the Arctic has melted faster this year than ever recorded before, according to the U.S. government's National Snow and Ice Data Centre (NSIDC). Arctic temperatures have risen more than twice as fast as the global average over the past half century. Last year saw the second greatest sea ice melt on record, 36% below the average minimum from 1979-2000. (The Guardian, 2012)
- **Mid-Atlantic Derecho Storm and Heat Wave:** An unusually strong, long-lived, and large straight-line wind storm called a derecho blew through Chicago to Washington at the end of June, 2012. The storm left millions without electricity in the midst of the record heat wave. The storm had energy readings five times that of normal thunderstorms. Fueled by the record high heat, this was one of the most powerful of this type of storm in the region in recent history. (Huffington Post, 2012)
- **Superstorm Sandy:** Hurricane Sandy made landfall on October 29, 2012, affecting more than 50 million on the east coast, from North Carolina to New England. A storm surge of nearly 14 feet hit the New York Harbor, causing widespread flooding, including subways. Sandy knocked out electricity for more homes and businesses than any other storm in history, according to the Department of Energy. Eqecat estimates the economic damage could reach $50 billion. (National Geographic, Huffington Post, 2012)

Epilogue References

Bloomberg, Afonso, S. and Mishra, P.; Monsoon Worst Since 2009 Threatening Sugar, Rice Crops, June 28, 2012, online at http://www.bloomberg.com/news/2012-06-27/monsoon-worst-since-2009-threatening-sugar-rice-crops.html.

CNBC, Domm, P.; Why You Should Watch Corn Prices for Next Two Weeks, June 27, 2012, online at http://www.cnbc.com/id/47887552.

Earth Snapshot, June 27, 2012; Russia Declares State of Emergency Due to Hundreds of Wildfires – June 27, 2012, online at http://www.eosnap.com/fires/russia-declares-state-of-emergency-due-to-hundreds-of-wildfires-june-27th-2012/.

Hindustan Times, June 28, 2012; Worst Floods in Assam Since 1998, Toll Mounts to 22, online at http://www.hindustantimes.com/India-news/Guwahati/Worst-floods-in-Assam-since-1998-toll-mounts-to-22/Article1-880381.aspx.

Huffington Post, Borenstein, S., July 3, 2012; Climate Change: U.S. Heat Waves, Wildfires And Flooding Are What Global Warming Looks Like, online at http://www.huffingtonpost.com/2012/07/03/climate-change-us-heat-wave-wildfire-flooding_n_1645616.html?utm_hp_ref=green.

Huffington Post, Craft, M., November 1, 2012; Hurricane Sandy's Economic Damage Could Reach $50 Billion, Eqecat Estimates, online at http://www.huffingtonpost.com/2012/11/01/hurricane-sandy-economic-damage_n_2057850.html.

International Business Times, Johanson, M., June 25, 2012; Colorado Wildfires Threaten Summer Tourism, online at http://www.ibtimes.com/articles/356195/20120625/colorado-wildfires-tourism.htm.

Meehl, G.A. and co-authors, 2009; Decadal Prediction: Can it be Skillful? Bull. Amer. Meteorol. Soc., 90, 1467—1485.

NASA, July 16, 2012; July 16, 2012 - Fires and Smoke in Eastern Russia, online at http://modis.gsfc.nasa.gov/gallery/individual.php?db_date=2012-07-16.

National Geographic, Drye, W., November 2, 2012; A Timeline of Hurricane Sandy’s Path of Destruction, online at http://newswatch.nationalgeographic.com/2012/11/02/a-timeline-of-hurricane-sandys-path-of-destruction/.

Reuters, Peltier, M., June 26, 2012; Tropical Storm Debby Rains Misery on Flooded Florida, online at http://www.reuters.com/article/2012/06/26/us-usa-storm-debby-idUSBRE85O0QT20120626.

RTT News, June 29, 2012; China Floods Leave 50 Dead, Over 10 Million Affected, online at http://www.rttnews.com/1914868/china-floods-leave-50-dead-over-10-million-affected.aspx?type=bn&Node=B1.

The Guardian, Vidal, J., June 27, 2012; Arctic Sea-ice Levels at Record Low for June," online at http://www.guardian.co.uk/environment/2012/jun/27/arctic-sea-ice-melt-rate?intcmp=122.

Acronym List

AMO	Atlantic Multidecadal Oscillation
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
AO	Arctic Oscillation
AR4	Fourth Assessment Report
CERES	Clouds and the Earth's Radiant Energy System
CFS	Climate Forecast System
CIESIN	Center for International Earth Science Information Network
CMAP	Climate Prediction Center Merged Analysis of Precipitation
CPC	Climate Prediction Center
CRUTEM	Climate Research Unit Temperature
DMSP	Defense Meteorological Satellite Program
DNI	Director of National Intelligence
DoD	Department of Defense
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGAR	Emissions Database for Global Atmospheric Research
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency
ERBE	Earth Radiation Budget Experiment System
ESRL	Earth System Research Laboratory
GCC	Global Climate Change
GHG	Greenhouse Gases
GISS	Goddard Institute for Space Studies
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Mission
GRACE	Gravity Recovery and Climate Experiment
Gt	Gigatons
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
KBS	Kara and Barents Seas
LL	Lower Left
LR	Lower Right
MEI	Multivariate ENSO Index
MJO	Madden Julian Oscillation
MSAP	Multi-Source Analysis of Precipitation
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation

NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Centre
PDI	Power Dissipation Index
PDO	Pacific Decadal Oscillation
SAM	Southern Annular Mode
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SSTs	Sea Surface Temperatures
TOA	Top of the Atmosphere
TOPEX	TOPography EXperiment for Ocean Circulation
TRMM	Tropical Rainfall Measuring Mission
TSP	Thermal State of Permafrost
UAV	Unmanned Aerial Vehicle
UCAR	University Corporation for Atmospheric Research
UL	Upper Left
UNEP	United Nations Environment Programme
UR	Upper Right
U.S.	United States
WG1	Working Group 1
WMO	World Meteorological Organization

Appendix: Workshop Participants

The Social Science Workshop on Societal Impacts of Near-Term Climate Stress was held on 16-17 November 2011 at Columbia University. Participants are listed in Table 1.

Table 1. Societal Impacts Workshop Participants.

PARTICIPANT	ORGANIZATION
Mr. Marc Levy	Center for International Earth Science Information Network
Dr. Arun Agrawal	University of Michigan
Dr. Jesse Ribot	University of Illinois at Urbana Champaign
Dr. Andrea Liverani	World Bank
Dr. Ted Parson	University of Michigan
Dr. Solomon Hsiang	Princeton University
Dr. Robert McLeman	University of Ottawa
Dr. Maria Lemos	University of Michigan
Dr. Mark Montgomery	SUNY Stonybrook
Dr. Mircea Dan Grigoriu	Cornell University
Dr. Chris Barrett	Cornell University
Dr. Nigel Arnell	Walker Institute for Climate System Research, University of Reading
Dr. Robert Bates	Harvard University

The Physical Science Workshop on Extreme Weather and National Security was held on 29 November 2011 at Harvard University. Participants are listed in Table 2.

Table 2. Physical Science Workshop Participants.

PARTICIPANT	ORGANIZATION
Dr. Michael McElroy	Harvard University
Dr. D. James Baker	Former Administrator, National Oceanic and Atmospheric Administration
Dr. Kevin Trenberth	Climate Analysis Section, National Center for Atmospheric Research
Dr. Kerry Emanuel	Massachusetts Institute of Technology
Dr. David R. Easterling	NOAA/National Climatic Data Center
Dr. Susan Solomon	University of Colorado at Boulder
Dr. Mark Cane	Lamont-Doherty Earth Observatory of Columbia University
Dr. Bill Schlesinger	Cary Institute of Ecosystem Studies
Dr. Leonard Smith	London School of Economics and Political Science
Dr. Ruby Leung	Pacific Northwest National Laboratory
Dr. Linda Mearns	Institute for the Study of Society and Environment, National Center for Atmospheric Research
Dr. Upmanu Lall	Columbia University
Dr. Vladimir Romanovsky	Geophysical Institute, University of Alaska Fairbanks
Dr. Natalie Mahowald	Cornell University

The Joint Workshop on Changing Weather: Implications for Global Stability and National Security was held on 16-17 February 2012 in Washington, DC. Participants are listed in Table 3.

Table 3. Joint Workshop Participants.

PARTICIPANT	ORGANIZATION
Dr. Michael McElroy	Harvard University
Dr. D. James Baker	Former Administrator, National Oceanic and Atmospheric Administration
Mr. Marc Levy	Center for International Earth Science Information Network
Dr. Jesse Ribot	University of Illinois at Urbana Champaign
Dr. Ted Parson	University of Michigan
Dr. Solomon Hsiang	Princeton University
Dr. Bill Schlesinger	Cary Institute of Ecosystem Studies
Dr. Leonard Smith	London School of Economics and Political Science
Dr. Vladimir Romanovsky	Geophysical Institute, University of Alaska Fairbanks
Dr. Ed Sarachik	University of Washington Seattle
Dr. James Anderson	Harvard University
Dr. Diana Liverman	Co-Director, Institute of the Environment
Dr. Neil Adger	University of Exeter
Mr. Robert Winokur	U.S. Navy
Dr. Lisa Goddard	Columbia University, International Research Institute for Climate and Society (IRI)
Dr. Bob Chen	Center for International Earth Science Information Network