West Antarctic Ice Sheet (Mass Balance) Summary

by

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Is the West Antarctic Ice Sheet (WAIS) growing or shrinking? Climate alarmists would have everyone believe that it is rapidly disappearing; while the *illuminati* -- Al Gore and James Hansen -- prophetically proclaim that we have but a few short years in which to (1) *repent* of our profligate usage of fossil fuels, (2) *preserve* the ice at the planet's southern pole by curbing our appetite for fossil-fuel energy and stopping global warming, and (3) *avoid* the catastrophic rise in sea level that would otherwise inundate the world's coastal lowlands. But are these zealots correct in what they preach? In what follows, we briefly review the findings of several researchers who have focused their attention on the *mass balance* of the WAIS in an attempt to help reason prevail over rhetoric in this important but contentious war of words.

Anderson and Andrews (1999) analyzed grain size and foraminiferal contents of radiometrically-dated sediment cores collected from the eastern Weddell Sea continental shelf and the western Weddell Sea deep-sea floor in an attempt to better understand the behavior of both the East and West Antarctic ice sheets. In doing so, their data led them to conclude that "significant deglaciation of the Weddell Sea continental shelf took place prior to the last glacial maximum," and that the ice masses that border the Weddell Sea today "are more extensive than they were during the previous glacial minimum." Hence, they concluded "that the current interglacial setting is characterized by a more extensive ice margin and larger ice shelves than existed during the last glacial minimum, and that the modern West and East Antarctic ice sheets have not yet shrunk to their minimum." It is thus to be expected -- independent of what global air temperature may currently be doing, because of the great inertial forces at work over much longer time scales -- that the modern East and West Antarctic Ice Sheets may well continue to shrink and release more icebergs to the Southern Ocean over the coming years, decades and centuries, thereby slowly raising global sea level. Nothing man has done is responsible for these phenomena, however; and nothing man can do will impact them in any way.

Also studying the combined ice sheets of both East and West Antarctica were Wingham *et al.* (1998), who used satellite radar altimeter measurements from 1992 to 1996 to estimate the rate of change of the thickness of nearly two thirds of the grounded portion of the entire Antarctic Ice Sheet, while using snowfall variability data obtained from ice cores to ultimately calculate the mass balance of the interior of the continental ice sheet over the past century. Their results showed that, *at most*, the interior of the Antarctic Ice Sheet has been "only a modest source or sink of sea-level mass this century." As a result, Wingham *et al.* concluded that "a large century-scale imbalance for the Antarctic interior is unlikely," noting that this conclusion is in harmony with a body of relative sea-level and geodetic evidence "supporting the notion that the grounded ice has been in balance at the millennial scale." This full set of findings thus suggests that both portions of the Antarctic Ice Sheet may be rather impervious to climate changes of the magnitude characteristic of the Medieval Warm Period and Little Ice Age, which is the type of change most likely to occur -- if there is any change at all -- in response to the ongoing rise in the air's CO_2 content.

In another study of all of Antarctica, Vaughn *et al.* (1999) used more than 1800 published and unpublished measurements of the surface mass balance of the continent to produce an updated assessment of yearly ice accumulation. Their results indicated that the "total net surface mass balance for the conterminous grounded ice sheet is 1811 Gton yr^{-1} (149 kg m^{-2} yr^{-1}) and for the entire ice sheet including ice shelves and embedded ice rises, 2288 Gton yr^{-1} (166 kg m^{-2} yr^{-1})." Since Vaughn *et al.* say "these values are around 18% and 7% higher than the estimates widely adopted at present," which were derived about 1985, they would seem to suggest that net icefall on Antarctica may well have been somewhat greater near the end of the 20th century than what was believed to have been the case a decade and a half earlier. Nevertheless, because of uncertainties in these numbers, as well as in those representing the total mass of ice lost from the ice sheet and ice shelves, the authors note that "we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea level change."

A year later, Stenoien and Bentley (2000) mapped the catchment region of West Antarctica's Pine Island Glacier, using radar altimetry and synthetic aperture radar interferometry. These data were used to develop a velocity map that revealed a system of tributaries that channeled ice from the catchment area into the fast-flowing glacier; and by combining the velocity data with information on ice thickness and snow accumulation rates, the two researchers were able to calculate an approximate mass balance for the glacier. Within an uncertainty of 30%, it was thereby determined that the mass balance of the catchment region was not significantly different from zero.

After three more years, Davis and Ferguson (2004) evaluated elevation changes of the entire Antarctic ice sheet over the five-year period June 1995 to April 2000, based on more than 123 *million* elevation change measurements made by the European Space Agency's European Remote Sensing 2 satellite radar altimeter. In doing so, they determined that the east Antarctic ice sheet had a five-year trend of 1.0 ± 0.6 cm/year, that the west Antarctic ice sheet had a five-year trend of -3.6 ± 1.0 cm/year, and that the entire Antarctic continent (north of 81.6°S) had a five-year trend of 0.4 ± 0.4 cm/year. In addition, the Pine Island, Thwaites, DeVicq and Land glaciers of West Antarctica exhibited five-year trends ranging from - 26 to - 135 cm/year.

In discussing their findings, Davis and Ferguson noted that the strongly negative trends of the coastal glacier outlets "suggest that the basin results are due to dynamic changes in glacier flow," and that recent observations "indicate strong basal melting, caused by ocean temperature increases, is occurring at the grounding lines of these outlet glaciers." Hence, they concluded "there is good evidence that the strongly negative trends at these outlet glaciers, the mass balance of the corresponding drainage basins, and the overall mass balance of the west Antarctic ice sheet may be related to increased basal melting caused by ocean temperature increases." Nevertheless, driven by the significantly positive trend of the much larger east Antarctic ice sheet, the ice volume of the entire continent grew ever larger over the last five years of the 20th century, the majority of which increase, according to Davis and Ferguson, was due to increased snowfall.

One year later, in an Editorial Essay published in the journal *Climatic Change*, Oppenheimer and Alley (2005) discussed "the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other," with respect to the WAIS and Greenland Ice Sheet (GIS). After a brief overview of the topic, they noted that "the key questions with respect to both WAIS and GIS are: What processes limit ice velocity, and how much can warming affect those processes?" In answer to these questions, they said that "no consensus has emerged about these issues nor, consequently, about the fate of either ice sheet, a state of affairs reflecting the weakness of current models and uncertainty in paleoclimatic reconstructions."

After a cursory review of the science related to these two key questions, Oppenheimer and Alley say their review "leads to a multitude of questions with respect to the basic science of the ice sheets," which we list below. However, instead of listing them in their original question form, we post them in the form of statements that address what *we do not know* about the various sub-topics mentioned, which is obviously what prompts the questions in the first place and validates the content of the statements.

(1) *We do not know* if the apparent response of glaciers and ice streams to surface melting and melting at their termini (e.g., ice shelves) could occur more generally over the ice sheets.

(2) *We do not know* if dynamical responses are likely to continue for centuries and propagate further inland or if it is more likely that they will be damped over time.

(3) *We do not know* if surface melting could cause rapid collapse of the Ross or Filchner-Ronne ice shelves, as occurred for the smaller Larsen ice shelf.

(4) *We do not know* if ice sheets made a significant net contribution to sea level rise over the past several decades.

(5) *We do not know* what might be useful paleoclimate analogs for sea level and ice sheet behavior in a warmer world.

(6) *We do not know* the reliability of Antarctic and Southern Ocean temperatures (and polar amplification) that are projected by current GCMs, nor do we know why they differ so widely among models, nor how these differences might be resolved.

(7) *We do not know* the prospects for expanding measurements and improving models of ice sheets nor the timescales involved.

(8) *We do not know* if current uncertainties in future ice sheet behavior can be expressed quantitatively.

(9) *We do not know* what would be useful early warning signs of impending ice sheet disintegration nor when these might be detectable.

(10) *We do not know*, given current uncertainties, if our present understanding of the vulnerability of either the WAIS or GIS is potentially useful in defining "dangerous anthropogenic interference" with earth's climate system.

(11) *We do not know* if the concept of a threshold temperature is useful.

(12) *We do not know* if either ice sheet seems more vulnerable and thus may provide a more immediate measure of climate "danger" and a more pressing target for research.

(13) *We do not know* if any of the various temperatures proposed in the literature as demarking danger of disintegration for one or the other ice sheet are useful in contributing to a better understanding of "dangerous anthropogenic interference."

(14) *We do not know* on what timescale future learning might affect the answers to these questions.

In concluding their essay, Oppenheimer and Alley describe this list of deficiencies in our knowledge of things related to the WAIS as "gaping holes in our understanding" that "will not be closed unless governments provide adequate resources for research," which seem just a bit self-serving. More importantly, however, they state that "if emissions of the greenhouse gases are not reduced while uncertainties are being resolved, there is a risk of making ice-sheet disintegration nearly inevitable."

Clearly, there is a chance -- be it ever so small -- that almost anything *could* occur. But how *probable* are such high-risk phenomena? To claim, as Oppenheimer and Alley do, that ice-sheet disintegration is *nearly inevitable* if emissions of greenhouse gases are not reduced, is *incredibly illogical*, especially in light of the existence of what they say are "gaping holes in our understanding," as enumerated in the above list. In fact, given the degree of deficiency in our knowledge of the matter, it is perhaps as likely as not that a continuation of the planet's recovery from the relative cold of the Little Ice Age could actually lead to a *buildup* of polar ice; but there is no way *we* would ever say that that outcome is "nearly inevitable."

The following year also saw the publication of a paper that had little to recommend its main conclusions. Velicogna and Wahr (2006) used measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the 34 months between April 2002 and August 2005. When all was said and done -- which included a lot of dubious approximations -- the two researchers concluded that "the ice sheet mass decreased significantly, at a rate of 152 ± 80 km^3/year of ice, equivalent to 0.4 ± 0.2 mm/year of global sea level rise," all of which mass loss came from the WAIS, since they calculated that the East Antarctic Ice Sheet mass balance was 0 ± 56 km^3/year.

What these results imply about the real world is highly dependent upon their ability to truly represent what they presume to describe; and in this regard Velicogna and Wahr say there is "geophysical contamination ... caused by signals outside Antarctica," including "continental hydrology ... and ocean mass variability." The first of these confounding factors, according to them, "is *estimated* [our italics] using monthly, global water storage fields from the Global Land Data Assimilation system," while "the ocean contamination is *estimated* [our italics] using a JPL version of the Estimating Circulation and Climate of the Ocean (ECCO) *general circulation model* [our italics]."

In addition to these problems, the two researchers note that the GRACE mass solutions "do not reveal whether a gravity variation over Antarctica is caused by a change in snow and ice on the surface, a change in atmospheric mass above Antarctica, or post-glacial rebound (PGR: the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years)."

To adjust for the confounding effect of the variable atmospheric mass above Antarctica, Velicogna and Wahr utilized European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological fields, but they acknowledge that "there are errors in those fields," so they "*estimate* [our italics] the secular component of those errors by finding monthly differences between meteorological fields from ECMWF and from the National Centers for Environmental Prediction."

With respect to post-glacial rebound, Velicogna and Wahr say "there are two important sources of error in PGR estimates: the ice history and Earth's viscosity profile." To deal with this problem, they "*estimate* [our italics] the PGR contribution and its uncertainties using *two* ice history *models* [our italics]."

All of these estimates and adjustments are convoluted and complex, as well as highly dependent upon various *models*. In addition, the estimates and adjustments do not deal with miniscule effects, as Velicogna and Wahr acknowledge that "the PGR contribution is much larger than the uncorrected GRACE trend." In fact, their calculations indicate that the PGR contribution exceeds that of the signal being sought *by nearly a factor of five!!!* And they are forced to admit that "a significant ice mass trend does not appear until the PGR contribution is removed."

In light of the latter *humungous* confounding problem, Velicogna and Wahr rightly state in their concluding paragraph that "the main disadvantage of GRACE is that it is more sensitive than other techniques to PGR." In fact, considering the many other adjustments they had to make, based upon *estimations* utilizing *multiple models* and *databases with errors* that had to be *further estimated*, we are led to totally discount the significance of their final result, particularly in light of the additional fact that it did not even cover a full three-year period. *Much* more likely to be *much* more representative of the truth with respect to the WAIS's mass balance are the findings of Zwally *et al.* (2005), who determined Antarctica's contribution to mean global sea level over a recent *nine*-year period to be only 0.08 mm/year compared to the five-times-greater value of 0.4 mm/year calculated by Velcogna and Wahr.

In a contemporaneous study, van de Berg *et al.* (2006) compared results of model-simulated Antarctic *surface mass balance* (SMB) -- which they derived from a regional atmospheric climate model for the time period 1980 to 2004 that used ERA-40 fields as lateral forcings -- with "all available SMB *observations* [our italics] from Antarctica (N=1900)" in a *recalibration process* that ultimately allowed them "to construct a best estimate of contemporary Antarctic SMB," where the many real-world observations employed in this process came from the studies of Vaughan *et al.* (1999), van den Broeke *et al.* (1999), Frezzotti *et al.* (2004), Karlof *et al.* (2000), Kaspari *et al.* (2004), Magand *et al.* (2004), Oerter *et al.* (1999, 2000), Smith *et al.* (2002) and Turner *et al.* (2002), which observations were derived by a number of different measurement techniques -- including stake arrays, bomb horizons and chemical analyses of ice cores that covered time periods ranging from a few years to more than a century.

As a result of this effort, van de Berg *et al.* determined that "the SMB integrated over the grounded ice sheet (171 ± 3 mm per year) exceeds previous estimates by as much as 15%," with the largest differences between their results and those of others being "up to one meter per year higher in the coastal zones of East and West Antarctica," concluding that "support or falsification of this result can only be found in new SMB observations from poorly covered high accumulation regions in coastal Antarctica." Consequently, until such time as pertinent new data might indicate otherwise, we have little reason to believe anything much different from what they have determined, i.e., that Antarctica's grounded ice sheet has been steadily growing for the past quarter-century.

In the very same year, Wingham *et al.* (2006) "analyzed 1.2 x 10^8 European remote sensing satellite altimeter echoes to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003," which survey, in their words, "covers 85% of the East Antarctic ice sheet and 51% of the West Antarctic ice sheet," which together comprise "72% of the grounded ice sheet." In doing so, they found that "overall, the data, corrected for isostatic rebound, show the ice sheet growing at 5 ± 1 mm per year." To calculate the ice sheet's change in *mass*, however, "requires knowledge of the density at which the volume changes have occurred," and when the researchers' best estimates of regional differences in this parameter were used, they found that "72% of the Antarctic ice sheet is gaining 27 ± 29 Gt per year, a sink of ocean mass sufficient to *lower* [their italics] global sea levels by 0.08 mm per year." This net *extraction* of water from the global ocean, according to Wingham *et al*., occurs because "mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica, exceed the ice dynamic mass loss from West Antarctica."

Also publishing in 2006, Ramillien *et al.* derived new estimates of the mass balances of the East and West Antarctic ice sheets from GRACE data for the period July 2002 to March 2005: a loss of 107 ± 23 km^3/year for West Antarctica and a gain of 67 ± 28 km^3/year for East Antarctica, which results yielded a net ice loss for the entire continent of only 40 km^3/year (which translates to a mean sea level rise of 0.11 mm/year), as opposed to the 152 km^3/year ice loss calculated by Velicogna and Wahr (which translates to a nearly four times larger mean sea level rise of 0.40 mm/year). Clearly, Ramillien *et al.*'s mean sea level rise is much less ominous than the much larger value calculated by Velicogna and Wahr; and it is of the same order of magnitude as the 0.08 mm/year Antarctic-induced mean sea level rise calculated by Zwally *et al.* (2005), which was derived from elevation changes based on *nine* years of satellite *radar altimetry data* obtained from the European Remote-sensing Satellites ERS-1 and -2. Even at that, the GRACE approach is still laden with a host of potential errors, as we noted in our discussion of the Velicogna and Wahr paper, and as both they and Ramillien *et al.* readily admit. In addition, as the latter researchers note in their closing paragraph, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations."

In yet another contemporary study, Remy and Frezzotti (2006) reviewed "the results given by three different ways of estimating mass balance, first by measuring the difference between mass input and output, second by monitoring the changing geometry of the continent, and third by modeling both the dynamic and climatic evolution of the continent." In describing their findings, the two researchers state that "the East Antarctica ice sheet is nowadays more or less in balance, while the West Antarctica ice sheet exhibits some changes likely to be related to climate change and is in negative balance." In addition, they report that "the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale," which they describe in terms of centuries. However, they note that "later, the precipitation increase will counterbalance this residual signal, leading to a thickening of the ice sheet and thus a decrease in sea level."

In one final study from 2006, van den Broeke *et al.* employed a regional atmospheric climate model (RACMO2), with snowdrift-related processes calculated offline, to calculate the flux of solid precipitation (Ps), surface sublimation (SU), sublimation from suspended (drifting/saltating) snow particles, horizontal snow drift transport, and surface melt (ME). In doing so, they found that "even without snowdrift-related processes, modeled (Ps-SU-ME) from RACMO2 strongly correlates with 1900 spatially weighted quality-controlled in situ SSMB *observations* [our italics]," which result they describe as "remarkable," given that the "model and observations are completely independent." Then, to deal with a remaining systematic elevation bias in the model results, they applied a set of empirical corrections (at 500-m intervals) that "largely eliminated" this final deviation from reality. And after analyzing all of the data-driven results for trends over the period 1980-2004, the four Dutch researchers report that "no trend is found in *any* [our italics] of the Antarctic SSMB components, nor in the size of ablation areas."

At long last, we finally move from 2006 to 2007, as we conclude our Summary with a brief review of the paper of Krinner *et al.* (2007), who used the LMDZ4 atmospheric general circulation model (Hourdin *et al.*, 2006) to simulate Antarctic climate for the periods 1981-2000 (to test the model's ability to adequately simulate present conditions) and 2081-2100 (to see what the future might hold for the mass balance of the Antarctic Ice Sheet and its impact on global sea level). This work revealed, first of all, that "the simulated present-day surface mass balance is skilful on continental scales," which gave them confidence that their results for the end of the 21st century would be reasonably skilful as well. Of that latter period a full century from now, they determined that "the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year," which corresponds "to a sea level decrease of 1.2 mm per year by the end of the twenty-first century," which would in turn "lead to a cumulated sea level decrease of about 6 cm." This result, in their words, occurs because the simulated temperature increase "leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air," where the extra moisture falls as precipitation, causing the continent's ice sheet to grow.

The results of this study -- based on sea surface boundary conditions taken from IPCC Fourth Assessment Report simulations (Dufresne *et al.*, 2005) that were carried out with the IPSL-CM4 coupled atmosphere-ocean general circulation model (Marti *et al.*, 2005), of which the LMDZ4 model is the atmospheric component -- argue strongly against climate-alarmist predictions of future catastrophic sea level rise due to mass wastage of the Antarctic Ice Sheet caused by CO2-induced global warming. In fact, they suggest just the *opposite*, i.e., that CO2-induced global warming would tend to *buffer* the world against such an outcome.

And that seems to be the message of most of the other major studies of the subject as well. We have nothing to fear but fear itself ... plus Al Gore and James Hansen, who seem to be its chief purveyors.

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