ICE SHEETS, GLOBAL WARMING, AND ARTICLE 2 OF THE UNFCCC

An Editorial Essay

1. Introduction

Rapid disintegration of the West Antarctic ice sheet (WAIS) was cited decades ago as a potentially severe consequence of global warming (Mercer, 1968, 1978; Revelle, 1983) and climate scientists have cast a wary eye toward the cryosphere ever since. Total loss of the West Antarctic or Greenland ice sheet (GIS) would cause eustatic sea level rise of 4–6 m and 7 m, respectively. The stability of the much larger East Antarctic ice sheet (EAIS) is sometimes questioned but it is likely that the two other ice sheets would disintegrate with less warming.

Initially, WAIS was the main focus of concern because as a marine ice sheet, it was thought by many to be inherently unstable (Oppenheimer, 1998). That WAIS has undergone a large reduction in area and perhaps in mass since the Last Glacial Maximum (Bindschadler, 1998; Huybrechts, 2002) provides evidence of its vulnerability to global temperature and sea level variations. In contrast, GIS is estimated to have shrunken by about 30% from its LGM volume (Fleming and Lambeck, 2004).

Disintegration of WAIS may provide a plausible example of "dangerous anthropogenic interference with the climate system" under Article 2 of the UN Framework Convention on Climate Change. In this context, two recent studies proposed specific temperatures and greenhouse gas concentrations (O'Neill and Oppenheimer, 2002, Oppenheimer and Alley, 2004) to be avoided. A key issue is 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.

A number of recent findings have refocused attention about ice sheet demise on Greenland, including the following: (1) the movement of the ice at one site has been tied to the availability of surface melt water, which percolates to and lubricates the ice sheet base (Zwally et al., 2002); (2) glaciers at the fringe of the ice sheet are almost uniformly losing mass at a rate about double that which can be ascribed to melting, and fast dynamical responses, including the lubrication mechanism, provide a plausible explanation of this discrepancy (Rignot et al., 2004a; Krabill et al., 2002; Thomas and PARCA, 2001); a different mechanism has been proposed for the rapid thinning of the Jakobshavn glacier, a response to melting of its small ice shelf due to warmed waters underneath (Thomas et al., 2003); (3) in one model simulation of the future extent of GIS, a steady-state mass balance could not be sustained for even a small ice sheet with a local warming greater than 3 °C (Church and Gregory, 2001); and (4) a refined paleotemperature estimate suggests that constant-elevation temperatures in central Greenland

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were 5–15 °C warmer than today during the Last Interglacial (LI), implying, using a different model, a much-reduced ice sheet at that time (Cuffey and Marshall, 2000).

In summary, the Greenland ice sheet is losing mass at its periphery faster than expected, and rapid-loss mechanisms have been identified at two locations that may conceivably operate broadly; even without including such rapid-loss mechanisms, models cannot produce a stable ice sheet above some local warming threshold, estimated in one set of simulations as 3 °C, (although disintegration times are on a millennium scale); and the LI, a potential analog in some respects for future climate, may have been too warm in Greenland to sustain an ice sheet any larger than a fraction of today's size.

At the same time, recent observations of rapid collapse of floating ice shelves along the Antarctic Peninsula and acceleration of neighboring glaciers (De Angelis and Skvarca, 2003; Scambos et al., 2004; Rignot et al., 2004b) have reinforced concern about the future stability of WAIS (Oppenheimer and Alley, 2004). Dynamical changes, including higher discharge, are also observed in glaciers terminating in Pine Island Bay in apparent response to loss of ice shelves due to basal melting (Rignot et al., 2002; Thomas et al., 2004). On the other hand, discharge through two ice streams draining into the Ross ice shelf has slowed on decadal timescales.

The speed of individual glaciers, up to 11 km/yr, may indicate the upper limit on how fast ice can drain from an ice sheet. If a large portion of either WAIS or GIS were to move that fast on a sustained basis, the ice sheet would disappear in about a century. The key questions with respect to both WAIS and GIS are: What processes limit ice velocity, and how much can warming affect those processes? Are the observed instances of apparent fast response to melting unique or could they become general over both ice sheets? Are they transient responses (van der Veen, 2001) that will be followed by re-adjustment over a few decades (e.g., as a result of processes like those that caused the recent slowdown of ice streams draining into the Ross ice shelf)? Unfortunately, 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 (see below).

2. A Danger Zone for Ice Sheet Disintegration?

Into this quagmire has leapt the fearless James Hansen with a decidedly novel perspective that attempts to leapfrog the complexities of ice sheet modeling. Rather, Hansen (2005) takes a global view based on Earth's energy budget. He argues that a progressively higher fraction of Earth's thermal imbalance resulting from greenhouse forcing will flow into melting of ice sheets. Hansen envisions that surface melt processes in Greenland of the sort identified by Zwally et al. (2002)

will enhance iceberg production, which would cool the high latitude ocean, reducing the normal radiation of heat there and further exacerbating the planetary radiation imbalance. An implied consequence would be enhanced tropical warming, greater water vapor feedback, and further ice sheet melting. Hansen points to Heinrich events as evidence that large planetary energy imbalances have been redressed in the past by rapid, massive ice sheet discharges, at least during the Pleistocence.

A second but no less radical conclusion of Hansen's argument is that a further global warming of 1 °C would place Earth in the cryosphere "danger" zone. Such a warming would arguably produce temperatures near those of past interglacial periods, particularly the LI. There is some evidence that global sea level stood up to 6 m higher then, and even higher during a previous interglacial, Stage 11, and the only plausible source for the water is one of the major ice sheets. The latter argument is not a new one. But Hansen asserts that the fast processes recently identified in GIS give this old point a new urgency because the timescale for ice sheet disintegration may be centuries rather than millennia, as often assumed. Hansen doesn't specify one ice sheet or the other as more at risk but his argument applies most obviously to GIS.

If Hansen is right about ice sheet response to the global energy imbalance and if IPCC's projections of future greenhouse gas concentrations prove correct, it would be too late to stem a catastrophic sea level rise, given the commitment to future warming already in the pipeline. Hansen finds a way out of the quandary produced by his inference of high ice sheet sensitivity. It is based on his earlier assessment that a dual strategy of halting or reversing the growth of non-CO_2 forcings (from methane, tropospheric ozone, etc.), while slowing CO_2 emissions could keep global warming from exceeding 1 °C (Hansen, 2004). There may be other reasons to maintain some hope of avoiding calamity, however.

Oppenheimer and Alley (2004) argued that a limit of either 2 °C or 4 °C global mean warming could be justified for WAIS. The upper temperature limit was determined by assuming that the major loss of grounded ice would occur into the Ross Sea rather than Pine Island Bay (and the Amundsen Sea) and then determining the point where melting on the Ross ice shelf was expected to become widespread. Extrapolating from the spectacular loss of the smaller Larsen ice shelf and the apparent response of neighboring glaciers, it was assumed that rapid fracturing of either of the two large ice shelves of WAIS would occur once melting on its surface became extensive, and that loss of a large ice shelf could trigger disintegration of the ice sheet. The lower temperature limit was determined in a similar manner to Hansen's approach, by assuming the ice sheet was lost during the LI, leading to a global sea level of about +6 m versus today. A "safe" global mean temperature change was estimated by scaling the maximum LI polar temperature (+3 °C vs. present) inferred from the Vostok ice core (Petit et al., 1999) using a polar amplification of 1–3. Whether the Vostok temperature differences also apply to West Antarctica remains an open question.

A truly global picture of mean temperature change during the LI has not emerged because paleoclimate proxies are sparse and their interpretation uncertain (McCulloch and Esat, 2000). But regardless of whether 1C or 2C warming provides a more reliable estimate, the different nature of past versus future forcing needs to be kept in mind in applying analogs. The key question is not "what global temperature may have led GIS or WAIS to disintegrate in the past?" Rather, we ought to ask "what future greenhouse forcing will bring about polar temperatures that may have caused ice sheet disintegration in the past?" To the extent that Hansen's one-degree limit is based on Greenland, it seems less than convincing because north polar amplification may well have been much greater during the LI. Recall the Cuffey and Marshall (2000) finding of a warming of 5–15 °C versus today in central Greenland. Is a 1 °C global warming now likely to produce so much warming there? GCM simulations would suggest otherwise. With regard to WAIS, it is unfortunate that Antarctic and southern ocean temperature simulations from GCMs are notoriously divergent.

3. Current Ice Sheet Behavior: A Sign of Fast Processes?

Another way to view the problem is to ask how the ice sheets have behaved in response to recent warming. Faster-than-predicted ice loss would indicate that processes are active that are not captured in models that predict gradual ice loss for the ice sheets in a warmer world. Ice elevation measurements based on aircraft and satellite altimetry combined with ground-based mass budgets indicate that both GIS and WAIS are losing mass, equivalent to 0.13 and 0.20 mm/yr, respectively (Rignot and Thomas, 2002). But uncertainties are very large (in our view, larger than several recent evaluations indicate, given that observational coverage is not yet comprehensive) and neither zero net loss nor several-fold larger ice loss, nor a slight overall gain for that matter, are excluded by the observations. In particular, accurate and widespread ice elevation measurements based on satellite radar and airborne laser altimetry are only available for the 1990s for both ice sheets. Not much can be said about the implications of such a short data set in regard to the response to greenhouse forcing, particularly since temperature trends have varied on a decadal scale in Greenland (Chylek et al., 2004) while for WAIS, only the Antarctic Peninsula has sufficient data to produce a representative trend.

But there is one telling piece of recent evidence, not mentioned by Hansen, which may support the case for fast response. The model-based central estimate of sea level increase for the 20th century falls 0.3 mm/yr below the range of uncertainty in averaged tide gauge measurements, leading to a "missing" sea level component (Church and Gregory, 2001). The question of whether tide gauge measurements are representative may have been laid to rest (Miller and Douglas, 2004). Furthermore, the ocean freshened over the second half of the 20th century by an amount sufficient to account for the missing component if the freshening originates in land-based ice (Munk, 2003).

It has been proposed that WAIS and/or GIS may be the source of the missing component of sea level rise (Jacobs, 1992; Miller and Douglas, 2004). If so, overall shrinkage of these ice sheets has indeed occurred over the past century faster than predicted by models. It may be coincidental that recent mass balance studies yield a total current negative balance of 0.33 mm/yr for WAIS and GIS combined, roughly equivalent to the "missing" sea level component over the past century.

Melting sea ice also contributes to salinity changes. A recent attempt to separate the components of freshening suggests a small or negative net ice sheet contribution (Wadhams and Munk, 2004) but has a significant shortcoming in combining and comparing trends from different periods. Furthermore, the authors are cautious in noting that low-salinity water from the Arctic is assumed in their analysis to mix instantaneously with the global ocean, a process that in reality could take decades. In addition, satellite-based measurements with the TOPEX and JASON instruments suggest a recent acceleration of the rise (Cazenave and Nerem, 2004). Although this change may simply reflect high frequency variability dominating the 10-year long record, it further complicates source attribution for sea level rise.

4. Paleoclimatic Analogs of Global Sea Level

How helpful are paleoclimatic studies in unraveling this puzzle? We know that part of East Antarctica was significantly warmer during the LI than the late Holocene (Petit et al., 1999), and central Greenland probably was as well. Beyond that, there is considerable disagreement among studies on both polar temperature and ice extent. Tarasov and Peltier (2003) estimate a climate for the LI that was not much warmer than today's and a sea level contribution of 2–5.2 m from the reduced volume of GIS, in contrast to the higher temperature and larger or near-total loss of the ice sheet (4–6.5 m sea level equivalent) suggested by Cuffey and Marshall (2000). As noted above, it is uncertain (within a degree or two) how much global temperatures during the LI differed from present values, and the same can be said of other recent interglacial periods, particularly Stage 11 which occurred around 400,000 yr BP (Droxler et al., 2002).

Local measurements of relative sea level indicate a +2 m to +6 m stand (Neumann and Hearty, 1996; Vezina et al., 1999) or higher during the LI and provide impetus for concern over the future consequences of warming. But local values must be adjusted for isostatic rebound of earth's crust and other local effects to obtain a global value for ice and seawater volume change (Peltier, 2002). Different approaches yield estimates of the change in sea level due to change in ice volume ranging from +0–5 m (Lambeck and Chappell, 2001) to +4–8 m (Rostami et al., 2000), as well as substantial disagreement over timescales of change. A rise of 2 m on a millennium timescale, for example, would be comparable to IPCC projections of future sea level rise attributable to slow shrinkage of GIS for a 3 °C warming. It would provide a challenge to societies but in most cases accommodation, if costly, would be possible. At the other extreme, a rise of 6 m in a few hundred years clearly satisfies the definition of "dangerous" proposed by Hansen and others.

Scherer et al. (1998) found remains of marine diatoms beneath WAIS well inland of the current grounding line, and proposed that they were deposited there subsequent to WAIS disintegration during Stage 11 when sea level may have stood at +20 m (Hearty et al., 1999). Others have suggested that the diatoms are windblown and not of local origin. Furthermore, the marine δ^{18}O record is inconsistent with higher sea level unless Stage 11 was cooler than the Holocene (Droxler et al., 2002), which presents a variety of conundrums including raising the issue of a "cold" collapse (MacAyeal, 1992).

Although these analogs suggest that WAIS and/or GIS (and possibly EAIS during Stage 11) were smaller during the Pleistocene, producing a higher sea level than today, they do not demand that most of WAIS or GIS disintegrated. Nor do they indicate which ice sheet contributed, nor how much, to sea level rise, nor how fast sea level rose. Nor do they provide a satisfactory measure of ice sheet sensitivity to temperature change.

5. GIS or WAIS?

Which ice sheet is more likely to have disintegrated in the past, and which is more likely to do so in a warmer world? Both GIS and WAIS currently may show small net losses of mass, although no overall relation to greenhouse forcing has been established. Yet extensive regions of both ice sheets exhibit unexpected, rapid motions of grounded ice, apparently in response to local melting that plausibly could be related to the global trend. Sea level trends of the past century provide evidence that one or both ice sheets are losing mass faster than current ice sheet models suggest, but do not discriminate between them. Cuffey and Marshall (2000) provide evidence of higher temperatures in central Greenland that would have led to a much smaller GIS during the LI; likewise, the findings of Scherer et al. (1998) suggest past shrinkage of WAIS. However, both interpretations have been challenged.

One piece of evidence seems to favor more immediate concern over Greenland: Current models, even absent fast processes, lead to a total loss of GIS for local warming >3 °C (Church and Gregory, 2001). In contrast, current models maintain WAIS up to nearly 10 °C local warming (Huybrechts and De Wolde, 1999). In the model world, sufficient forcing to destroy an ice sheet would be set in place for GIS (Gregory et al., 2004) long before it would be for WAIS. But current models may be less realistic for WAIS than for GIS. Ice streams, the major dynamical features of WAIS, are not adequately captured by the models. Basal melting under the ice shelves in the Pine Island Bay area already appears to be having a marked effect on both the floating ice and the lower reaches of the ice streams there. Whether and how soon a modest global warming would affect the basal temperatures is entirely unclear; current models are too crude to answer these questions.

Most important, no clear answer is provided by existing paleoclimate evidence to the key question of the potential rate of disintegration of either ice sheet. This is a question that is likely to be answered only by improved models, refined analysis of the paleo-record or, unfortunately, by the experience of ice sheet collapse.

6. Key Questions

The foregoing discussion leads to a multitude of questions with respect to the basic science of the ice sheets as well as its implications for interpreting and implementing Article 2. With respect to science, key questions include:

- Could the apparent response of glaciers and ice streams to surface melting and melting at their termini (e.g., ice shelves) occur more generally over the ice sheets?
- Are dynamical responses likely to continue for centuries and propagate further inland or is it more likely that they will be damped over time?
- What is the likelihood that surface melting could cause rapid collapse of the Ross or Filchner-Ronne ice shelves, as occurred for the smaller Larsen ice shelf?
- What is the likelihood that ice sheets made a significant net contribution to sea level rise over the past several decades?
- What are useful paleoclimate analogs for sea level and ice sheet behavior in a warmer world?
- How reliable are Antarctic and Southern Ocean temperatures (and polar amplification) projected by current GCMs, why do they differ widely among models, and how might these differences be resolved?
- What are the prospects for expanding measurements and improving models of ice sheets, and on what timescale?
- Can the current uncertainties in future ice sheet behavior be expressed quantitatively?
- What would be useful early warning signs of impending ice sheet disintegration and when might these be detectable?

Some key questions pertinent to Article 2 are:

- Given the uncertainties, is current understanding of the vulnerability of either ice sheet potentially useful in defining “dangerous anthropogenic interference” in the context of Article 2?
- If so, is the concept of a threshold temperature useful?
- Does either ice sheet seem more vulnerable, and thus provide a more immediate measure of climate “danger,” and a more pressing target for research?

- Are any of the various temperatures proposed in the literature as demarking danger of disintegration for one or the other ice sheet (1 °C, 2 °C, or 4 °C global warming or 10 °C local warming) useful in contributing to a better understanding of "dangerous anthropogenic interference" under Article 2?
- Would a probability density function (Mastrandrea and Schneider, 2004) for ice-sheet disintegration based on current understanding be more useful than the binary approach to danger underlying the Hansen, as well as the Oppenheimer and Alley (2004) assessments, or are uncertainties so large that such an approach is premature?
- On what timescale might future learning affect the answers to these questions?

7. Implications for Policy

During 2005, governments will begin to discuss future commitments under the UN Framework Convention on Climate Change. Without additional constraints on greenhouse gas emissions, it appears that both WAIS and GIS, particularly the latter, eventually could become vulnerable to complete disintegration due to forcing that may accumulate over this century. Yet the timescales of their potential contribution to sea level rise are unknown and may remain so for decades. Regardless of whether 1 °C, 2 °C, 4 °C global warming, or 10 °C local warming, or some other value turns out to be a useful limit in the context of Article 2, delay in reducing emissions would substantially increase the risk of entering the danger zone. The gaping holes in our understanding will not be closed unless governments provide adequate resources for research. But 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. Then avoidance of global calamity may depend on strategies like pumping carbon dioxide out of the atmosphere (Lackner, 2003). But it may not be possible to deploy such "overshoot" approaches fast enough (O'Neill and Oppenheimer, 2004) if rapid ice sheet process are already a reality.

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Woodrow Wilson School of Public
and International Affairs and
Department of Geosciences
Princeton University
448 Robertson Hall, Princeton
New Jersey 08544, U.S.A.
E-mail: omichael@princeton.edu
MICHAEL OPPENHEIMER

Department of Geosciences and
Earth and Environmental Systems Institute
Pennsylvania State University
517 Deike Bldg, University Park
Pennsylvania 16802, U.S.A.
E-mail: rba6@psu.edu
R. B. ALLEY