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The Future of the West Antarctic Ice Sheet: Observed and Predicted Changes, Tipping Points, and Policy Considerations

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Abstract: The State of WAIS Science

1. If the West Antarctic Ice Sheet (WAIS) disintegrated, it would raise global sea level by 3.3-6 meters. The uncertainty is due to differing views on the extent of instability of a marine based ice sheet. The period of time over which this rise would occur (or its rate) is uncertain.
2. Two recent studies estimate future global sea level rise of 0.75-1.9 meters and 0.8-2.0 meters by 2100 (Vermeer and Rahmstorf 2009, Pfeffer et al. 2008).
3. A 2002 expert elicitation project gave a 5% likelihood of a rapid disintegration of WAIS within the next 200 years (Vaughan and Spouge); a more recent publication states that a rapid disintegration is more likely than that (Katz and Worster 2010).
4. While there may be a tipping point for WAIS, it is just as likely that there is no tipping point, but that WAIS would gradually lose ice in a warming world. Some models suggest that WAIS could gain ice for some period of time if snowfall increases rapidly but ice loss is slow.
5. There is a range of estimates of the temperature of a potential tipping point. One paper (Alley and MacAyeal 1993) suggests that the WAIS could already be destined for collapse independent of anthropogenic global warming. Several studies estimate anywhere from 1 to 5°C above current global temperatures as a threshold for WAIS instability (Hansen et al. 2008, Keller et al. 2005, Kriegler et al. 2009. Kopp et al. 2009, Lenton et al. 2008, Mercer 1978). The existence of such a tipping point would not resolve the question of how fast sea level rise would occur.
6. Disintegrations at the floating Wordie, Wilkins, and Larsen A and B Ice Shelves have been observed. Glaciers in the Amundsen Sea/Pine Island Bay, are changing rapidly. Among the Ross Sea/Siple coast glaciers, some ice streams are accelerating while others have stalled. Other areas of the ice sheet show no change.
7. The most recent measurements indicate that the Antarctic ice sheet is losing mass, and this loss, largely from the Antartic Peninsula and West Antarctica, is accelerating.
8. Key areas of observational research include: the role of subglacial lakes and other water flowing at the base of the ice, and ice streams in regulating discharge; ocean-ice interactions; and continental and ocean warming.

1 Introduction

Climate scientists and policy makers are concerned with the ice sheets in Antarctica and Greenland because of their potential contribution to global sea level rise, which could possibly occur rapidly enough to challenge the ability of parts of society to adapt effectively. This paper provides an update of the scientific literature, including subjective research, on the West Antarctic Ice Sheet (WAIS) since the deadline for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). It includes model-based, empirical, and expert elicitation research methods to determine the state of WAIS science, and contemporary predictions on WAIS tipping points and melting rates. The paper includes research based upon satellite remote sensing, field observations, paleo-climatology, and ice sheet models. In addition, the paper briefly explores future research plans that may provide a more complete understanding of the past, present, and future of the West Antarctic Ice Sheet.

WAIS is potentially unstable and holds enough ice to raise global sea level between 3.3-6 meters (Alley and Whillans 1991, Bamber et al. 2009, Lythe et al. 2001). However, determining the likelihood and rate of a hypothetical WAIS disintegration has proven difficult. In the Fourth Assessment Report (AR4) IPCC, expert authors review scientific literature in their climate change specialty and provide policy-relevant science advice, including projections to the year 2100. In regards to the West Antarctic Ice Sheet, the authors determined that there was not enough information to provide projected rates at which WAIS could contribute to sea level rise (SLR) in the next 100 years (2007). There was more agreement about WAIS instability in millennial timescales.

The four IPCC assessments have consistently found characterization of the future of WAIS and its contribution to sea level rise to be extremely challenging. While a range of plausible rates of sea level rise from the Antarctic Ice Sheets was discussed in the Third Assessment Report (TAR) of the IPCC, the quantitative upper limit on the rate provided, 3mm per year, or 3 meters in 1,000 years (2001), was deduced from a model with known limitations. In the Fourth Assessment Report (AR4), the combined Greenland and WAIS contribution to 21^{st} century sea level rise was estimated based on the assumption that ice sheet loss would not accelerate, as well as an additional sensitivity test involving modest acceleration. The decision to not use model-based estimates arose from greater understanding of the limitations of ice sheet models (O'Reilly 2009). Similarly, the rate of sea level rise beyond the 21^{st} century was left highly uncertain.

There is no overall consensus on the future of WAIS in the glaciological community, though there is extensive cooperation and coordinated research, and much is agreed upon in terms of the history of WAIS and interpretation of recent observations. The Scientific Committee on Antarctic Research (SCAR) provided a comprehensive section on the West Antarctic Ice Sheet in *Antarctic Climate Change and the Environment* (ACCE), stating that "for the moment there are no comprehensive, objective projections that can be cited, and the future evolution of the Antarctic ice sheet is better described through a more subjective, discursive approach" (Turner et al. 2009: 344). This paper builds upon this suggestion from the ACCE, providing a subjective, discursive approach along with a scientific literature review, and provides policy-oriented suggestions relating to the future of the West Antarctic Ice Sheet and increased sea level rise.

There is general agreement that more field observations and improved modeling capabilities are needed to provide an accurate understanding of how the ice sheet works and how it may behave in the future. However, due to the large potential impact of WAIS on global sea level, many experts believe it is necessary to proceed with climate policies that take into account the information available on the WAIS, including both the potential for extreme outcomes and the large uncertainties and gaps in our knowledge and in any assessment of the risk.

2 An Overview of the West Antarctic Ice Sheet

Most of Antarctica's land mass is covered by ice sheets, either the larger East Antarctic Ice Sheet (EAIS) or the West Antarctic Ice Sheet (WAIS). Combined, the Antarctic ice sheet has a volume of 25.4 million km^3. An ice sheet is "a glacier of considerable thickness and more than 50,000 square kilometers in area, forming a continuous cover of snow and ice over a land surface, spreading outward in all directions and not confined by the underlying topography" (American Geological Institute 2010, online). Mass accumulates on the ice sheet through precipitation (snow) and is lost principally through subglacial melting, surface melting and iceberg formation, as well as sublimation. While the East Antarctic Ice Sheet contains about 90% of Antarctica's ice (Lythe and Vaughan 2001), the EAIS is usually considered relatively stable in both the near and long terms, absent a very large warming far exceeding projected warming for this century. However, rapid ice loss from EAIS has been observed at a few locations (Chen et al. 2009, Rignot 2006, Rignot et al. 2008), the significance of which is not yet known.

West and East Antarctica (Vaughan and Spouge 2002: 67)

WAIS is of more immediate concern because it is a marine ice sheet - much of the ice sheet rests on a bed below sea level. Mercer (1968, 1978) was the first glaciologist to call attention to the potential instabilities of the West Antarctic Ice Sheet, and calculated the contribution of WAIS to sea level to be 5 meters. Mercer's 1978 article, "West Antarctic Ice Sheet and CO_2 greenhouse effect: a threat of disaster," prompted increased research on WAIS. For a period of time it was widely believed that WAIS would become unstable if its large ice shelves melted in a warming world. Then, early ice sheet models and mass balance calculations suggested that WAIS was stable in at least the short term, and some estimates found that WAIS was accumulating mass rather than losing it (i.e., having a negative affect on sea level rise at the current time). New research since the late 1990s has reversed the weight of expert opinion, with instability now regarded as a plausible outcome of global warming, with one sector, the Amundsen Sea area, a target of immediate interest in this regard.

The West Antarctic Ice Sheet has relatively quick-moving areas called ice streams within the ice sheet. Ice streams have been extensively studied, particularly those draining into the Ross Sea from the Siple coast. The ice streams sit upon a bed of viscous, clay-like till that deforms easily and can cause ice to slide far more rapidly that ice frozen to bedrock. However, their behavior is complex in space and time. For example, Ice Stream C (Kamb Ice Stream) has been immobile for the last 150 years (Conway et al. 2002) while the other nearby ice streams are moving towards the sea. Understanding the mechanics of the ice streams is challenging: and as will be described in the section below, this lack of observational information makes building realistic models difficult.

Many WAIS ice streams discharge into floating ice shelves. The collapse of an ice shelf does not raise global sea level: this ice is already in the ocean, so it does not contribute more water. However, the collapse of an ice shelf can affect the ice sheets on the continent, which would contribute to sea level rise. For example, DeAngelis et al. (2003) and Rignot (2004) observed that the glaciers behind Larsen B sped up after it collapsed. Once the buttressing ice shelves were removed, the continental ice flowed more quickly into the ocean. This ice does contribute to increased sea level. Even before a glacier has lost much of its ice to the sea, glaciologists can observe changes, often described as thinning, acceleration, and ungrounding. Thinning suggests that the glacier is melting. Acceleration indicates that the glacier is flowing more quickly towards the sea. And a shift of the grounding line towards the continental center suggests that the feature maybe unstable.

3 The State of the Science

The state of WAIS science here is organized according to some of the key scientific debates: 1) estimating WAIS' potential contribution to sea level rise, 2) determining tipping points for WAIS disintegration, 3) observed regions where rapid changes are occurring, 4) key vulnerabilities, 5) modeling the ice sheet, 6) and future directions for WAIS research. The WAIS research community is interdisciplinary and cooperative, and many key researchers are coordinating efforts to create models that transcend current limitations in order to effectively depict ice sheet behavior. These limitations arise from our inability to represent how ice flows. Modelers' ability to represent surface melting is believed to be more robust. As will be described below, this is difficult work because of challenges in representing the physics and geology of WAIS as well as a lack of observations of the ice sheet. However, great strides have been made since the last IPCC report: this work will be reviewed below, followed by a discussion about future research that will allow credible predictions of WAIS' behavior to be made.

As a note, the IPCC Fourth Assessment Report (2007) concluded that the planet has already experienced warming of about 0.74°C in the past 100 years. Currently, greenhouse gas concentration in the atmosphere exceeds 385 parts per million (ppm) of CO_2. The globally averaged temperature is projected to rise between 1.1-6.4°C above 1990 levels by the year 2100 depending on emissions scenarios and climate sensitivity. Unless otherwise noted, sea level rise figures given below are estimates of the global average. Temperature projections are from an approximate "present" point—already 0.74°C above pre-industrial temperatures. It is estimated that the Antarctic Peninsula has warmed approximately 0.5°C per decade for the past 50 years, while WAIS and the continent overall have warmed at a lower rate (Steig et al. 2009). The Southern Ocean has also been observed to be warming, freshening, and changing its circulation patterns (Turner et al., 2009).

3.1 WAIS' Potential Contribution to Sea Level Rise

Mercer suggested that the disintegration of WAIS would lead to 5 meters of global sea level rise (1978), and since then, various authors have reached similar estimates of 4-6m based on approximations for the amount of ice bedded below sea level. However, a recent study by Bamber et al. (2009) employed improved assessments of the location of the continental bed and also considered its configuration to determine which areas of West Antarctica were most vulnerable to rapid disintegration. The authors also used recent models of the solid earth response to ice sheet disintegration, rather than assuming, as earlier investigators had, that the effect of ice loss from WAIS would be identical at all coastlines. Importantly, Bamber et al. categorized much of the ice that was previously thought to be vulnerable, as stable, concluding that the previous calculations overestimate WAIS' contribution to global average sea level rise, which they estimated as 3.3 meters (2009). While this figure represents a global average, higher local sea level rises were estimated for coastlines along North America and the Indian Ocean, as well as at other locations. The Bamber estimate highlights the ongoing uncertainty over how much of WAIS is vulnerable to warming. Due to the methodology used, Bamber's estimate of the contribution of WAIS' disintegration to global sea level rise may be regarded as a likely lower limit on what might actually occur should WAIS disintegrate. Without a more accurate model, deep uncertainty will remain.

Of course, even a definitive estimate of WAIS' susceptible volume would not provide the entire story. The essential policy-relevant questions are:

(1) How fast could the disintegration of WAIS occur?
(2) At what rate could sea level rise at particular coastlines, accompanying a WAIS disintegration?
(3) What is the likelihood of this happening at all, beginning when, under what assumptions about warming?

In the absence of enough information to provide model-based predictions for the future of WAIS, it can be helpful to look at alternative methods. One such approach is called expert elicitation, where experts on a subject are queried to provide an assessment of what they know, what they do not know, and what their sense of the future is (Morgan and Henrion 1990). Expert elicitation may be carried out in a variety of forms. With model-based experiments not yet capable of producing a credible probability (in terms of either a probability density function or a cumulative probability function for WAIS collapse), some researchers have turned to expert elicitation for enlightenment.

Vaughan and Spouge (2002) conducted an expert elicitation study of WAIS specialists to discern their opinions on WAIS disintegration. They polled an interdisciplinary panel of specialists to determine the consensus view, presenting their findings in probabilistic form. They found that "while the overall opinion of the panel was that WAIS most likely will not collapse in the next few centuries, their uncertainty retains a 5% *probability* of WAIS causing sea level rise at least 10 mm/year within 200 years" (65). Two more recent expert elicitation studies (Lenton et al. 2008 and Kriegler et al. 2009), discussed in more detail below, have provided additional insight into expert opinion on WAIS. The degree to which expert elicitation is useful is controversial.

Recent projections of global sea level rise have used various estimation methods, including empirical techniques, in place of model-based approaches. Rahmstorf et al. (2007) and Vemeer and Rahmstorf (2009) projected a rate of sea level rise (SLR) increase that implicitly assumes that ice sheet melting will accelerate, rather than stay the same over time. They estimated a range of 75-190 centimeters above 1990 levels by 2100 (2009:1). Pfeffer et al. (2008) explores the maximum rates that ice might move using a hypothesis for maximum speed, arriving at a range of 0.8-2.0m of mean global sea level rise by 2100, with the upper end of the range regarded as probably unrealistic. Several other recent analyses find outcomes in the same range. For comparison, AR4 projected a range of 0.18-0.59m for this century with a possible additional adjustment of 10-20 cm to account (crudely) for ice sheet dynamics. None of these estimates explored sea level rise beyond 2100, and they are not universally accepted.

3.2 Tipping Points

Policy makers have asked scientists to identify "tipping points" in the WAIS and elsewhere to help target climate change policies to avoid truly dangerous outcomes. How warm can the planet get before the WAIS disintegrates to the point that it would not recover, even if global temperatures later cool? Tipping points in the ice sheet "exist if the ice does not recover from a certain ice loss caused by climatic warming even if the climatic forcing were to return to the colder conditions that existed before the onset of that specific ice loss"

(Notz 2009; following Eisenman and Wettlaufer 2009 and Lenton et al. 2008). Therefore, a tipping point is usually expressed in degrees of warming and affiliated with a particular threshold of atmospheric carbon dioxide and its equivalents. Unless otherwise specified, degrees of warming indicate average global warming above 1990 levels.

Before proceeding, we must note that a tipping point in temperature terms does not indicate how quickly the ice sheet would disintegrate or the rate at which it would contribute to sea level rise. Though the earth system could reach the WAIS tipping point during this century, the melting and subsequent sea level rise might lag significantly by centuries. Also, it must be noted that Alley and MacAyeal (1993) suggested that it was possible that WAIS may be destined to collapse in the next few centuries regardless of anthropogenic climate change due to natural internal oscillations of the ice, though they did not provide a "tipping point".

It also should be noted that perhaps there is not a specific "tipping point," or catastrophic threshold, for the West Antarctic Ice Sheet. Instead, there may be a continuum of changes from small to catastrophic that will occur as the planet warms. Nonetheless, they are a convenient tool to convey risk. This section looks at potential tipping point scenarios, though there is not widespread consensus on this matter.

Mercer's findings (1968, 1978) "led to the inference that disintegration of WAIS may have caused sea level to rise at least once during a period when global mean temperature may not have reached more that 2°C above that of today" (Oppenheimer 1998: 325). Therefore, the earliest studies had estimated that WAIS would collapse at relatively low temperatures, though these estimates have not been consistent over the past 40 years.

Following Mercer, several glaciologists looked at how long the complete disintegration of WAIS would take once the tipping point is reached. Their opinions may have changed over time and in light of rapidly emerging observations. Estimates for collapse from present included timescales of 400 years (Thomas et al 1979), 500 years (Bentley 1982), 500-1200 years with a rate of 80-120 cm/ century (Bindschadler 1997), and 1600-2400 years with a rate of 25 cm/ century (MacAyeal 1992). This vast range for WAIS disintegration underscores the broad scope of opinions and uncertainty about WAIS behavior and models, which continues today.

A lower limit on the tipping point of about 2°C global warming above current temperatures remains a common assumption (Keller et al 2005, Oppenheimer 2008, O'Neill and Oppenheimer 2002), and provided part of the basis for long term objective embodied in the Copenhagen Accord. Such a warming is likely to occur under several AR4 scenarios by 2100. The mechanism might be triggered by disintegration of ice shelves brought about by either surface warming, or intrusion of warm water below the ice shelves.

Part of the evidence for the vulnerability of WAIS comes from paleoclimatic data used to determine sea levels when WAIS did not exist or was significantly smaller than today. Kopp et al. (2009) use the last interglacial—approximately 125 kyr ago—as a partial analog for 1-2°C global warming scenarios. In such scenarios, the poles are considered to have been 3-5°C warmer than present. Kopp et al. concluded that it is likely that, in this slightly warmer time, the Greenland Ice Sheet and the West Antarctic Ice Sheet were substantially smaller than their present size, and that global sea level was very likely (95% probability) 6.6 meters and likely (67% probability) 8.0 meters higher than today, though unlikely (33% probability) to have been as much as 9.4m higher. This study demonstrates the "long-term vulnerability of ice sheets to even relatively low levels of sustained global warming" (863). The authors also noted that there is currently a sufficient concentration of greenhouse gasses in the atmosphere to cause an eventual global warming of 1.4-3.2°C (863). We can infer from this that we could already be at, or rapidly approaching, the tipping point for WAIS disintegration, though the authors indeed note that analog between the paleoclimate and the contemporary climate is partial: there may be other factors that could delay the disintegration of the ice sheets, or render the analog inappropriate. And the time issue remains: how long do temperatures have to remain over the tipping point, and how long is the lag between increased temperature and ice loss?

Some studies look at tipping points not from a WAIS perspective but in terms of the entire planet. Hansen et al (2008) look at paleoclimate data to discern that when the Earth had above 450 +/- 100 ppm CO_2, the planet was ice-free. They suggest a target level of 350 ppm atmospheric CO_2 (today there is 385ppm) to preserve the contemporary state of the planet, including the ice sheets, and note that declines in ice volume would happen quickly (1). In essence, the authors are calling for no more than 1°C warming, with partial reversal of current greenhouse gas concentrations.

Kriegler et al (2009) reach a different conclusion than Hansen et al (2008) in their expert elicitation study, which aimed to estimate the likelihood of one of the following systems changing: El Niño-Southern Oscillation, the Amazon rainforest, the Greenland and West Antarctic Ice Sheets, and the Atlantic meridional overturning circulation, finding it likely that at least one of these events would occur with a 2-4°C warming, and even higher probabilities with 4°C and higher warming (1). The wide range of probability estimates generated for WAIS specifically showed high uncertainty among the participants (4).

Another study (Lenton et al 2008) combines a literature review with an expert elicitation in discussing "tipping elements," of which WAIS is one. In it, the authors estimate that West Antarctica could disintegrate with 5-8°C of local warming, which is associated with 3-5°C global warming. The authors also noted that "rapid sea level rise (>1 m per century) is more likely to come from the WAIS than from the GIS [Greenland Ice Sheet]" (1789). In addition, Lenton et al also discuss a technique for an early warning system to detect when tipping points have been reached (1792).

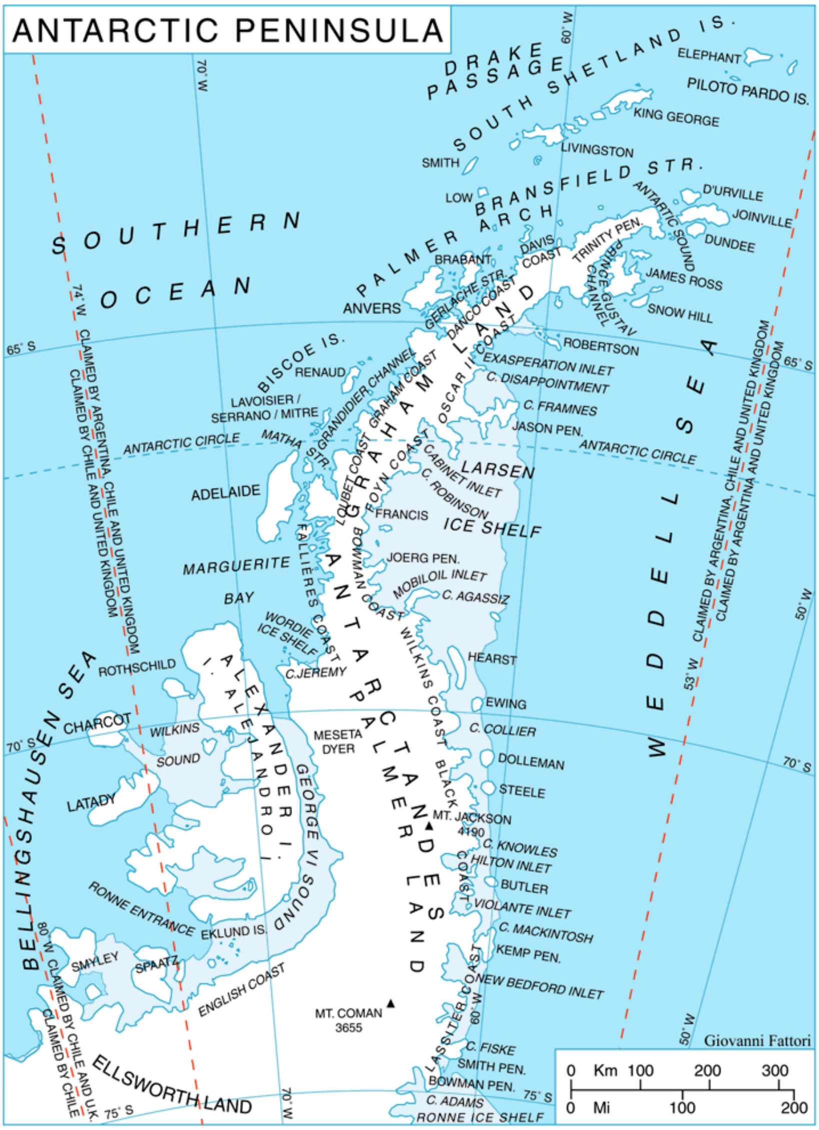
An assessment commissioned by the World Wildlife Fund and Allianz, and written by Lenton, Footitt, and Dlugolecki summarizes WAIS tipping points, among others. They conclude that WAIS is likely to reach its tipping point if global temperature rises another 3-5°C. However, a recent elicitation (Kriegler et al 2009, discussed above) suggests that the tipping point would be reached if global temperatures reach 2-4°C above 1980-1999 temperatures. The authors give a "worst case scenario" of WAIS disintegration in less than 300 years, raising sea level by about 5 meters (2009:11), assuming emissions remain similar to present levels and a relatively clear understanding of ice mechanics.

Overall, WAIS tipping points have been estimated to range from 1-5°C and to cause a potential sea level raise of 3.3-6 meters.

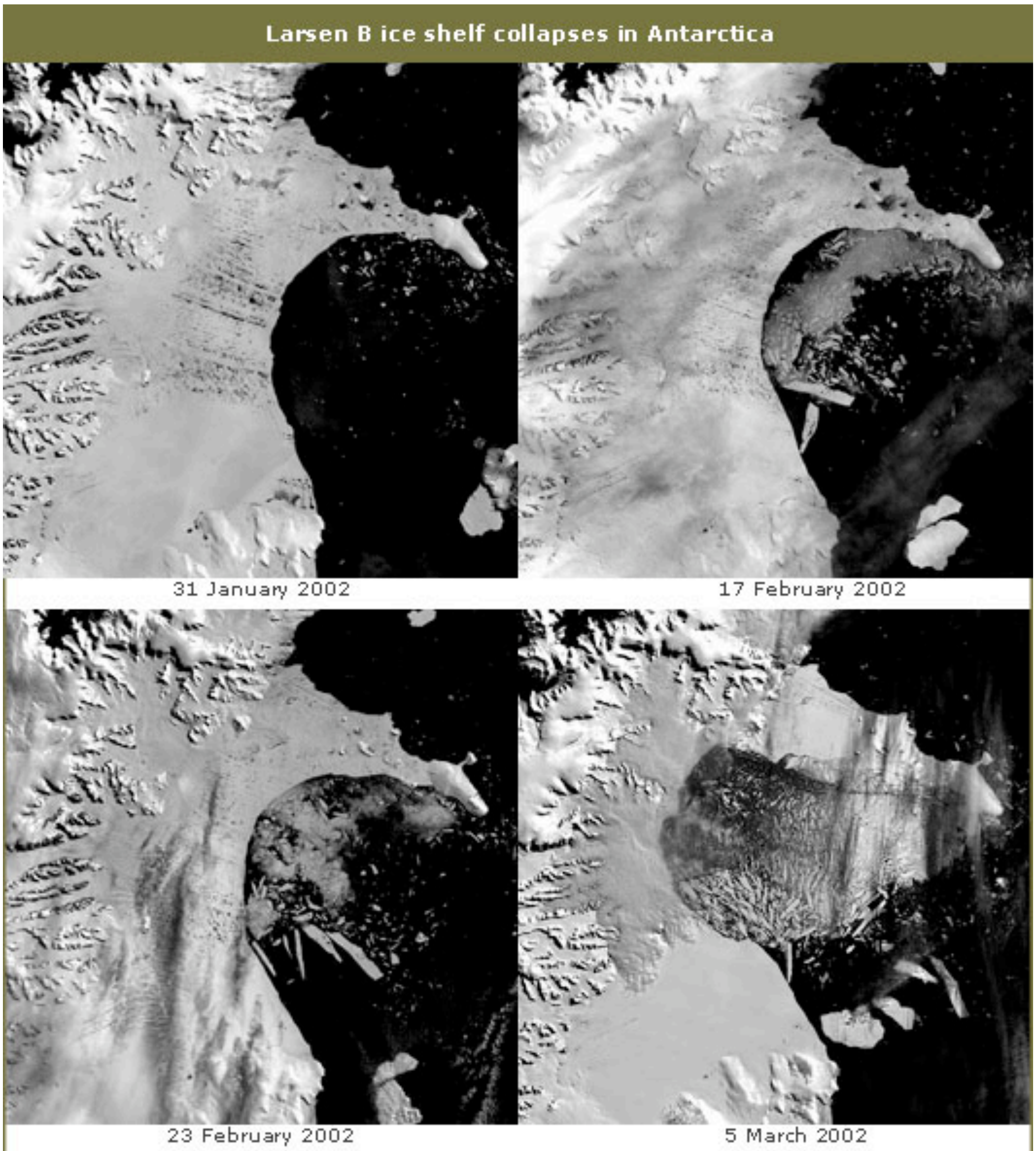
3.3 Observed Rapid Changes

In Antarctica, some rapid changes have occurred that may help us understand how and how quickly the ice sheet could disintegrate. Ice shelves, which are parts of the ice sheet lying over the ocean, have been found to have a climate "limit for existence". When the surfaces of ice shelves are exposed to persistently warmer temperatures – higher than an annual mean temperature of -5°C or monthly mean January temperature of 0°C - they disintegrate (Rott et al 1996, Vaughan and Doake 1996, Doake 1998).

The Wordie Ice Shelf on the Antarctic Peninsula disintegrated since the 1960s, and now is the first ice shelf to have disappeared completely (Ferrigno et al 2008). Doake and Vaughan (1991) noted that rapid disintegration began with the appearance of meltwater ponds on the ice shelf's surface and noted risks of disintegration for the Wilkins, Larsen, and George VI ice shelves. Doake and Vaughan also wrote that "substantial additional warming would be required before similar processes could initiate breakup of the Ross and Filchner-Ronne ice shelves, which help stabilize the West Antarctic Ice Sheet" (328).



One of the most studied ice shelf collapses is that of the Larsen B ice shelf, located on the Antarctic Peninsula. Nearby Larsen A collapsed in 1995 (Rott et al. 1996, Vaughan and Doake 1996). Larsen B was located near the northern limit of the continent, in an area that has shown marked, persistent warming. In 2002, the northern part of Larsen B ice shelf collapsed in less than 6 weeks, demonstrating how quickly near-permanent ice could disintegrate (Hulbe 2002). The collapse of Larsen B also drew considerable public attention to the effects of anthropogenic warming in Antarctica.



Note: Satellite imagery analyzed in early 2002 revealed that the northern section of the Larsen B ice shelf had disintegrated and separated from the continent within a 35-day period.
Source: Moderate Resolution Imaging Spectroradiometer (MODIS), NASA Terra satellite, National Snow and Ice Data Center, University of Colorado (nsidc.org/iceshelves/larsenb2002/)

The Amundsen Sea sector of the WAIS seems to be the most rapidly changing part of the ice sheet. The Amundsen Sea is located further to the south than the Antarctic Peninsula, and the changes in the area seem to be triggered by the ocean, not atmospheric temperature. Ice streams in the Ross Sea sector have been observed to accelerate and decelerate, and to thin as well as to thicken (Alley and Whillans 1991, Joughin et al 2002); there are no long-term records that show this behavior in the Amundsen Sea sector. In this area, Pine Island Glacier has been observed to be accelerating, thinning, and un-grounding (Shepherd et al 2004, Rignot 2006, Rignot 2008). Nearby Smith Glacier is also observed to be accelerating and un-grounding, while neighboring Thwaites is not accelerating, but widening—also a sign of warming-related instability (Rignot 2008). Payne et al. note that Pine Island Glacier could noticeably thin and accelerate on a decadal timescale, and that there is a strong response from the ice sheet in entirety where it encounters a warmer ocean at its face (2004). In looking at Pine Island Glacier, Shepherd et al concluded that "Antarctica is more sensitive to changing climates than was previously considered" (2004: 1). Rignot expects that mass loss from the Pine Island Bay region, currently very small, to "grow considerably larger in years to come" (2008:1). Wingham et al. (2009) have studied the thinning of Pine Island Glacier through time and space, using satellite observations, and estimate that the main trunk of the Pine Island Glacier could be afloat in the next 100 years. The collapse of Pine Island Glacier could be a trigger for a larger disintegration of WAIS (Rignot et al 1998).

Two key questions surrounding events in the Amundsen Sea are: how well do these cases translate into describing what could happen with the entire WAIS system? How would the disintegration of one WAIS sector affect the rest of the ice sheet? While there is a relatively small amount of ice behind the Larsen ice shelf, the ice in the Amundsen Sea area could add about 1.5m to sea level if it all disintegrated (Vaughan 2008).

3.4 Key Vulnerabilities and Sites of Observation

One key area of inquiry is the mass balance of Antarctic ice as a whole. Until very recently, observations suggested that Antarctica had been in balance (not losing or gaining mass) or gaining mass (Alley et al 2005). The increased snowfall that was thought to cause the apparent mass gain was attributed to warming Antarctic temperatures. However, more recent measurements from NASA and the German Aerospace Center, Deutsches Zentrum für Luft und Raumfahrt's Gravity Recovery and Climate Experiment (GRACE) satellite show that the Antarctic ice sheet is actually losing mass (Rignot et al. 2008, Chen et al. 2009) and that this loss has accelerated between 2002 and 2009 (Velicogna 2009). While WAIS appears to be losing mass, it is more difficult to ascertain whether EAIS is in or out of balance.

One way in which observations have improved over recent years is through the complementary application of satellite observations to the more local field-based glaciological studies. By observing the entire continent through satellite altimetry, glaciologists discovered subglacial lakes and channels of water underneath the ice sheet. These lakes periodically drained and filled, sometimes rapidly (Fricker et al. 2007). This discovery could help researchers explain how the WAIS could become less stable and eventually disintegrate, with basal water playing a lubricating role.

How the ice sheet interacts with the warming ocean is also a major focus: some experts consider this to be the primary mechanism for ice sheet collapse. Payne et al. (2004) suggested that there is a strong response from the ice sheet when it encounters the warming ocean, with perturbations at the grounding line propagating quickly upstream (see also Jacobs et al. 1996, Jenkins et al. 1997, Rignot 1998, Shepherd et al. 2004). Heat from Circumpolar Deep Water (CDW) flows towards the ice sheet, and provides enough heat to account for most of the basal melting in the Amundsen Sea area (Thomas et al. 2008, Walker et al. 2007). Grounded ice responds indirectly to the ocean's heat via the effect of ice shelf thinning. It is essentially akin to a slow-motion version of glacier acceleration that follows the disintegration of an ice shelf (see Larsen B example, above).

Antarctica's climate is also a significant factor. Mayewski et al. (2009) have written a comprehensive report on the state of Antarctica's climate system, including its paleoclimate and snowfall, mass balance, and weather figures for West Antarctica. Steig et al. (2009) used calibrated weather data to create a comprehensive overview of Antarctic surface temperatures in the past 50 years. They determined that West Antarctica is warming by approximately 0.1°C per decade. While this is partially offset by fall cooling in East Antarctica, there remains slight warming trend for the continent as a whole.

3.5 Modeling the West Antarctic Ice Sheet

There are currently no continental-scale ice sheet models that are considered to be reliable enough for prediction of decadal or century-scale changes. However, modelers over the past three decades have built smaller-scale models using the information available. The pace of recent new observations have shown some key weaknesses in present-day models.

As described above, a key issue is the inability to realistically represent rapid ice flow, like those of ice streams: there is simply not yet enough observational information or physical understanding to model this adequately. The diverse behavior of ice streams across time and space emphatically demonstrates that the ice sheet cannot be considered a monolithic chunk of ice with consistent and persistent behavior: realistic physical responses to climate entail understanding ice streams, subglacial lakes and channels, and the bed, among other features.

Another pivotal problem is whether the grounding line, the boundary between grounded and floating ice, is stable. Weertman (1974) had suggested this problem early on in WAIS research. Recently, Schoof presented a boundary layer theory that provides physical equations representing the grounding line (2007). His calculations support Weertman's theory of WAIS instability at the grounding line under some circumstances but the relevance of these to the real ice sheet remains unclear. Using a different set of approximations, Katz and Worster (2010) infer that an unstable grounding line recession may already be occurring in the Pine Island Bay. They also note that, in contrast to Vaughan and Spouge, discussed above (2002), that "the scenario of unstable grounding-line recession on retrograde beds in West Antarctica is likely" (2010: 22). However, even if the grounding line question was solved, the issue of the timing and rate of a WAIS disintegration remains. The WAIS research and climate policy communities look forward to these results being incorporated into the next generation of ice models.

3.6 The Future of WAIS Research

Research on the West Antarctic Ice Sheet, including field and satellite observations as well as model development, is interdisciplinary. The United States-based WAIS Initiative and the Forum for Research into Ice Shelf Processes, a European-based Scientific Committee on Antarctic Research (SCAR) subcommittee, meet annually to provide scientists for opportunities for collaboration and information sharing.

Several groups are building new ice models. One, called CISM: the Community Ice Sheet Model, is based on the earlier GLIMMER model. CISM will have open access to the model code, providing a flexible framework for trying out different approaches to modeling the ice sheet simultaneously (Rutt et al 2009). CISM provides the ice component to the Community Climate System Model, which contributes to IPCC projections. CISM scientists have agreed to prioritize their modeling efforts towards issues that will contribute a more accurate understanding of future sea level rise, with a goal to provide information for the Fifth Assessment Report of the IPCC (Lipscomb et al. 2009). A European effort called ice2sea (www.ice2sea.eu) has an explicit set of deliverables for the next and future IPCC reports. Climate research groups around the world are looking to integrate next-generation models with climate models. Other teams are taking a bottom-up approach to understanding key processes, such as ice-ocean interaction and hydrology.

4 Policy Considerations

4.1 Proceeding Under Uncertainty

Uncertainties, defined as "imprecision in the characterization of any outcome," surround the future of the West Antarctic Ice Sheet (Oppenheimer 2008: 153). A rapid disintegration of WAIS is a high-impact event with uncertain, but likely low, probability. However, the probability of ice loss is likely to increase over time, particularly if CO2 and other greenhouse gas emissions continue to rise at projected rates.

How can we balance the desire to decrease uncertainties by additional learning with the need to minimize risks to large portions of the human population?

First, we can examine the different kinds and levels of uncertainties about WAIS. There is *model uncertainty*, inherent to the act of using numerical models to predict the future (Patt 1999, 2007). While this type of uncertainty can be minimized to some extent with improved models and the data that contribute to it, there is always a possibility of omitted, unknown process which could disrupt any predictions. Another key kind of uncertainty is *conflict uncertainty,* in which experts disagree (Patt 1999, 2007). Such contention can occur for a multitude of reasons: a lack of data, differences in theoretical orientations, personal comfort level with risk, social dynamics among the experts, and the ways in which scientific publications and programs are organized and managed (O'Reilly et al 2010). While conflict uncertainty may always exist to some degree, it can be greatly minimized through improved information and consensus building over time.

For WAIS, model uncertainty may be reduced as more and more precise observational data are used to evaluate the models (although negative learning experience suggests the outcome may be otherwise for a period of time). With conflict uncertainty, the timeframe and rate of a future rapid disintegration is highly uncertain. But there is a bigger picture—that of inherent WAIS instability, observations of small-scale rapid disintegrations of ice shelves, thinning, accelerating and ungrounding glaciers, and observations showing Antarctica as a warming continent, losing ice at an accelerated rate—that is more certain.

Uncertainty is sometimes portrayed as a lack of consensus. In the IPCC's AR4 on the WAIS issue, this is an adequate characterization. The authors determined that there simply was not enough reliable information to trust model results: there was a lack of consensus among the WAIS community. This report relied heavily on models and left the ice sheets out of the sea level rise table, prominently boxed off in the Summary for Policy Makers (2007: 13). While the text contained caveats that explained the potential high risk of WAIS disintegration, these were not included anywhere in the table (Oppenheimer et al. 2007). As a result, the table gives the misleading impression of a consensus about the insignificance of WAIS to future sea level rise. The table and the figures contained within it are given a more prominent discursive location than the text that explains more of the nuances of the WAIS problem, which at minimum makes it difficult to communicate the uncertainties to policy makers. In turn, this makes it difficult to create informed policies (Oppenheimer et al. 2007). Improved articulation and communication of uncertainties, coupled with improved scientific literacy among non-experts, is needed.

4.2 Preparing for extreme outcomes/ worst-case scenarios

Another crucial factor to consider when reading scientific assessments with fairly wide projections is which scenarios should determine future adaptive planning. While planning for adapting to low- to mid-range sea level rise scenarios is probably simpler and more cost-effective in the short term, we encourage more attention to be focused on extreme outcomes, outliers, and worst-case scenarios. Even though such events are less likely, the environmental and socioeconomic effects of worst-case scenarios and extreme outcomes are monumental and potentially devastating. This is, in essence, a precautionary approach towards low-probability, high-risk events.

4.3 Policy Recommendations

As shown above, some research suggests that we have already, or are near to, emitting enough CO_2 and other greenhouse gases to produce a tipping effect for the WAIS. The question that remains is: how rapid is the response once the tipping occurs? There are gaps in scientific research, both observationally and theoretically based. Therefore, if we take a precautionary approach, it is necessary to make policy decisions to reduce anthropogenic climate change impacts at the same time that more research is being conducted. WAIS should be factored into all decisions about slowing, reversing, mitigating, and adapting to anthropogenic global warming.

International climate treaties cannot be negotiated in the Antarctic Treaty System. However, Antarctic Treaty Consultative Parties (ATCPs) can use their scientific and logistical expertise to execute the following steps:

- Because Antarctic managers and scientists have the unique position of being in Antarctica in the event of a rapid disintegration of an ice shelf or part of the grounded ice sheet (or another short-term, high impact event), ASOC suggests that ATCPs: **coordinate a response strategy from which to rapidly deploy personnel and equipment to observe and record changes in the ice sheets as they occur.**

- Since adaptation and mitigation strategies rely on timely information about the sea level rise and other key climate change factors, ASOC suggests that ATCPs: **encourage the creation and establishment of an early detection system that could alert us when WAIS has experienced or is expected to immanently experience a local disintegration.** The existing fleet of satellite altimetry projects and equipment may be enough to coordinate this.

- Because there is still high uncertainty surrounding WAIS behavior, and because there is a lack of reliable ice models, ASOC suggests that ATCPs**: expand and strongly support research efforts by Antarctic scientists studying the history, behavior, and future of the West Antarctic Ice Sheet,**

so that the best available scientific evidence may continue to inform impending climate policies.

- ASOC strongly supports global reductions in greenhouse gases, mitigation of the effects on climate change on the world's ecosystems and human communities, and thoughtful planning that takes climate change impacts into account for all Antarctic activities. ASOC acknowledges the world-class climate research produced by Antarctic researchers and supports dissemination of these findings to policy makers as well as to the world population in general.

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