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# West Antarctic Ice Sheet collapse – the fall and rise of a paradigm

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## Abstract

It is now almost 30 years since John Mercer (1978) first presented the idea that climate change could eventually cause a rapid deglaciation, or "collapse," of a large part of the West Antarctic ice sheet (WAIS), raising world sea levels by 5 m and causing untold economic and social impacts. This idea, apparently simple and scientifically plausible, created a vision of the future, sufficiently alarming that it became a paradigm for a generation of researchers and provided an icon for the green movement. Through the 1990s, however, a lack of observational evidence for ongoing retreat in WAIS and improved understanding of the complex dynamics of ice streams meant that estimates of likelihood of collapse seemed to be diminishing. In the last few years, however, satellite studies over the relatively inaccessible Amundsen Sea sector of West Antarctica have shown clear evidence of ice sheet retreat showing all the features that might have been predicted for emergent collapse. These studies are re-invigorating the paradigm, albeit in a modified form, and debate about the future stability of WAIS. Since much of WAIS appears to be unchanging, it may, no longer be reasonable to suggest there is an imminent threat of a 5-m rise in sea level resulting from complete collapse of the West Antarctic ice sheet, but there is strong evidence that the Amundsen Sea embayment is changing rapidly. This area alone, contains the potential to raise sea level by around ~1.5 m, but more importantly it seems likely that it could, alter rapidly enough, to make a significant addition to the rate of sea-level rise over coming two centuries. Furthermore, a plausible connection between contemporary climate change and the fate of the ice sheet appears to be developing. The return of the paradigm presents a dilemma for policy-makers, and establishes a renewed set of priorities for the glaciological community. In particular, we must establish whether the hypothesized instability in WAIS is

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real, or simply an oversimplification resulting from inadequate understanding of the feedbacks that allow ice sheets to achieve equilibrium: and whether there is any likelihood that contemporary climate change could initiate collapse.

## 1 Background

In a series of traverses across Antarctica begun during the last International Geophysical Year (1957–1958), glaciologists discovered that much of the West Antarctic Ice Sheet (WAIS, Fig. 1) rests on a bed that is mostly below sea level. Indeed, the bed topography is like a bowl, sloping down from the edge of ice sheet into a deep rift beneath its interior (Bentley 1964) – if the ice sheet were removed, most of the area would be inundated by the sea. For this reason glaciologists described WAIS as a "marine ice sheet," and they were quick to see a particular significance in this configuration. With a bed below sea level, the ice sheet is anchored to its bed only because it is too thick to float. WAIS is the only significant marine ice sheet left on Earth, and it was suggested that this is because marine ice sheets are intrinsically unstable (Weertman 1974; Thomas and Bentley 1978), perhaps unable

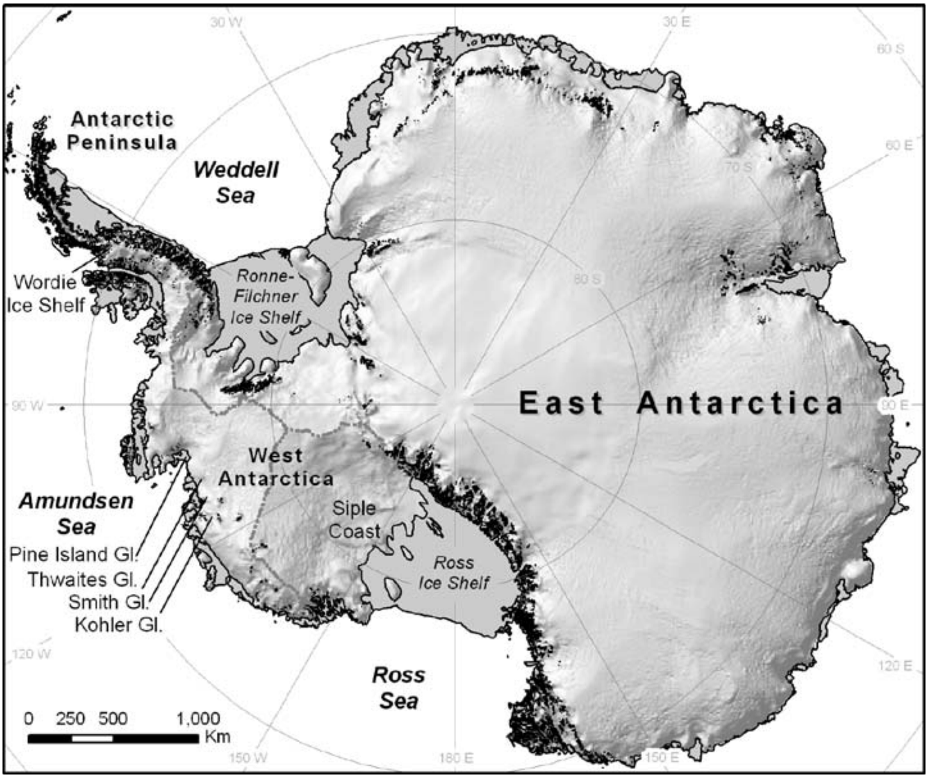

**Fig. 1** Map of Antarctica. The dotted line shows the ice-divides separating ice-flow into Ross Ice Shelf through the Siple Coast, into the Weddell Sea through Ronne–Filchner Ice Shelf, and through the glaciers and narrow ice shelves into the Amundsen Sea

to achieve the balance between accumulation of snowfall, and its removal by ice-flow. If areas around the margin of a marine ice sheet were to lose contact with the bed, there would be a reduction in the force that restrains ice-flow. Ice-flow could then accelerate and leave an imbalance between outflow and replenishment by snowfall. This imbalance would, in turn, cause thinning of the ice sheet at the point at which it begins to float, allowing the so-called, grounding line, to retreat inland. It was argued that this could set up a positive-feedback cycle that could be sufficiently strong to overcome the negative feedbacks that act to keep ice sheets in a state of balance. Once this positive-feedback cycle was set in motion, ice-sheet "collapse" or "disintegration" would inevitably follow and with severe global consequences since WAIS contains sufficient ice to raise global sea level by about 5-m (Lythe et al. 2001).

Thus the concept of the instability of marine ice sheets was already established when, almost 30 years ago, Mercer (1978) sought to connect the future of WAIS with the emerging idea that emissions of $CO_2$ caused by human activities would promote global warming. In this paper, I discuss the hypothesis presented by Mercer, and how it became a paradigm guiding Antarctic glaciology for much of the 1980s and 1990s. I chart why, in the late-1990s, with the absence of observational evidence of change, the paradigm appeared to be in decline. I provide an overview of the plethora of new satellite studies in the 1990s and 2000s that has now provided evidence for ongoing change in the portion of WAIS that most concerned Mercer, and has reinvigorated the debate about the risk that WAIS will substantially contribute to sea-level rise in coming centuries. I conclude by summarizing the current understanding and arguing that elements of the paradigm presented by Mercer are once again emerging to as research priorities, albeit incorporating modified mechanisms of ice-sheet retreat and modified magnitudes and timescales of risk.

## 2 Deconstructing Mercer's paradigm

Mercer's paradigm (Mercer 1978) can be summarized as suggesting that a rapid loss of much of WAIS could be triggered by anthropogenic climate warming. He believed that ice shelves restrain ice-flow inland of the grounded ice, and so the initiation of WAIS collapse might be relatively easy if the floating ice shelves were to be lost. He went on to argue that ice shelves were particularly sensitive to climate and their removal could come about quickly due to atmospheric warming, and proposed a particular mechanism by which this could happen.

Mercer argued that while normally, the temperature inside an ice shelf remains close to the mean annual air temperature (see, Paterson 1994), but if melt water is produced at the surface, it can percolate down into the ice (either through the porous ice, Vaughan et al. 1993; or within crevasses, see, Scambos et al. 2000). When this water refreezes the latent heat released can raise the temperature of considerable volumes of ice to the melting point. Where this effect was significant, "temperate ice shelves", waterlogged, and lacking any structural strength, would be formed, and these could not survive indefinitely. Effectively, wherever summer temperatures caused significant melt, the ice shelves would be lost.

In essence, the hypothesis that Mercer had constructed, and which through repetition became a paradigm, was that WAIS was dependent for its stability on the presence of ice shelves around its margins, those ice shelves might be vulnerable to warming, and due to the potential instability of marine ice sheets, anthropogenic warming could eventually cause complete loss of WAIS.

Although Mercer's original discussion was couched in terms of the "rapid deglaciation" of WAIS, the more arresting shorthand of "collapse" and "disintegration" has been more frequently been associated with the theory; these dramatic terms have always provoked visions of an almost immediate, or imminent, and complete loss of WAIS, and with it the often repeated threat of a 5-m rise in global sea level. Actually, Mercer did not put a clear timescale on how long this might take. Rather, he presented an inconclusive, and in hindsight, over-simplistic discussion based on "polar amplification," the greatly magnified warming in high latitudes predicted by early general circulation models (GCMs) as the equilibrium response to $CO_2$-doubling. He completely sidestepped the question of how long it would take to remove the ice shelves, and then how long it would take for the ice sheet to collapse, although he did go on to suggest that a "dangerous warning sign" that WAIS-collapse was close at hand would be climate warming on the Antarctic Peninsula and an accompanying retreat of ice shelves in that area.

The likely timescales for complete removal of WAIS are probably rather longer than might be interpreted from either Mercer's discussion, or indeed, the thousands of news articles that have since been produced surrounding this issue. Only a few glaciologists consider it likely that complete collapse of WAIS could occur in less than a few centuries, although most agree that a thousand-year timescale for collapse is possible (Vaughan and Spouge 2002). This timescale might be initially less alarming than that implied by word "collapse," but it still allows for a highly significant rate of sea-level rise. Indeed, recent studies of the impacts of sea-level rise have suggested that it is the *rate* of sea-level rise that is the key factor in determining the magnitude of the hazard (e.g. Nicholls and Lowe 2004), and that realistic stabilization targets should be based on the maximum rate of sea-level rise rather than on stabilization of sea-level rise per se (Nicholls and Lowe 2006). So, even if it took 1,000 years, a collapse of WAIS would represent a very significant hazard by causing substantial rates of sea-level rise, perhaps at times approaching those achieved during deglaciation at the end of the last interglacial period.

## 3 Evidence of past ice-sheet collapse

It is worth noting that in one sense the rapid deglaciation of marine ice sheets is more than just a hypothesis – it has undoubtedly occurred before. A key piece of evidence among many is the sea level record derived from corals. This record shows two separate periods at the end of the last glacial period when global sea level rose at rates of more than 1 m per century (e.g., Fairbanks 1989). One of these was almost certainly caused by deglaciation of the marine ice sheets in the northern hemisphere, although it is also possible, that one resulted, at least in part, from changes in Antarctica (e.g. Clark et al. 2002).

## 4 The Antarctic Peninsula red-herring

Mercer's warning that a sign that "dangerous warming" had begun would be retreat of ice shelves around the Antarctica Peninsula, appears to have been added as an afterthought in the original paper, and as far as deglaciation of WAIS is concerned I believe that it is a red herring. It is, however, worth some discussion, because the specific prediction about the Antarctic Peninsula has turned out to be astonishingly accurate.

Mercer predicted that an atmospheric warming would cause migration of summer melting conditions south, along the climatic-gradient on the Antarctic Peninsula, resulting in retreat of ice shelves. He noted that he already had evidence that retreat had begun on Wordie Ice Shelf, but notwithstanding this prior knowledge about one ice shelf, the pattern of retreat predicted by Mercer is exactly the one we have since observed around the Antarctic Peninsula (Vaughan and Doake 1996; Morris and Vaughan 2003). Indeed, analysis of new and historical data has shown the progressive retreat of ten separate ice shelves during the latter part of the twentieth century. A few retreats culminated in a final-stage break-up which was both rapid and dramatic.

Several mechanisms for both retreat and collapse have been suggested (e.g., Doake et al. 1998; MacAyeal et al. 2003), and retreat of, at least one ice shelf may have been accompanied by thinning resulting from ocean melting (Shepherd et al. 2003), but as the pattern of ice shelf retreat followed precisely the pattern predicted by Mercer (Vaughan and Doake 1996; Morris and Vaughan 2003), there is wide acceptance that ice shelf retreat is primarily driven by atmospheric warming, where that warming initiates surface melting. Indeed there is strong evidence that such a warming has been continuing across the Antarctic Peninsula for at least 50 years (Vaughan et al. 2003), and that there has been a consequent increase in the volume of summer melting (Vaughan 2006).

Despite this correlation, there are, however, several reasons that the retreat of these ice shelves around the Antarctic Peninsula should not be considered to be a bellwether for the much larger WAIS. Firstly, while the Antarctic Peninsula has been warming at an exceptional rate, 3.7 ± 1.6°C per century (Vaughan et al. 2003), the existence of warming over the rest of the Antarctic continent is equivocal. Eleven long-term climate records from across Antarctica show warming, while eight show cooling (Turner et al. 2005). And while it can be argued that Antarctic coastal climate records do show modest warming (0.8 ± 1.4°C per century[1]), which is in line with mean global warming without any clear "polar amplification", this is considerably less than the warming seen on the Antarctic Peninsula. Secondly, most of the ice shelves around WAIS are, even in the warmest summers, still several degrees Celsius below from the melting conditions: considerable further warming will be required before those ice shelves are threatened – perhaps several centuries into the future at the present rate. Without melt water to advect heat into the ice shelf, the process of conduction alone would need many thousands of years to transmit surface temperature changes through the ice. Thus, the specific mechanism that Mercer envisaged as making WAIS vulnerable to climate change now appears to be unlikely to become significant in the near future, and the parallels with changes on the Antarctic Peninsula, while theoretically valid, are not likely to become a reality for several centuries.

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[1] This is the simple mean of the 11 trends from Antarctic coastal stations not on the Antarctic Peninsula given in Table 1, of Vaughan et al. (2003).

## 5 Field campaigns in WAIS during the 1980s and 1990s

The unsurprising interest in the potential instability of WAIS, born from Mercer ideas, focused the efforts of much fieldwork throughout the 1980s and 1990s. European efforts were largely directed towards Filchner–Ronne Ice Shelf and its hinterland (www.gfi.uib.no/forskning/frisp/), while US researchers concentrated on Ross Ice Shelf and Siple Coast (http://igloo.gsfc.nasa.gov/wais/). The remaining third of the ice sheet, draining into the Amundsen Sea, remained largely unvisited; beyond the normal logistical scope of any national operator, and supposedly with such terrible weather conditions that field operations would be near to impossible. Without belittling the achievements of those programmes – they have dramatically improved every aspect of our understanding of ice streams and ice shelves – neither programme produced any strong evidence that collapse of those portions of WAIS was imminent or even possible. Although it should be noted that the ice streams on the Siple Coast were shown to exhibit considerable decadal and centurial variability (for a summary see, Anandakrishnan et al. 2001) and consequent local imbalance (Joughin and Tulaczyk 2002). Indeed, several modelling and theoretical studies emerged suggesting that the presence of ice streams, with their curious intermediate ice-sheet/ice-shelf dynamics, could stabilize the grounding line of a marine ice sheet (e.g., Hindmarsh 1996). These suggested that the potential for WAIS to collapse was misjudged, or at least it was overstated as an inevitable response to minor change, rather than a remote possibility, to which the ice sheet could be driven only in extremis. Similarly, other studies showed that the retreat of the ice sheet on the Siple Coast in response to changing conditions at the end of the last glacial period, was anything but catastrophic, taking many thousands of years and perhaps continuing to the present (Conway et al. 1999; Stone et al. 2003).

## 6 The decline of the paradigm

Thus towards the end of the 1990s, even though the Antarctic Peninsula was warming fast and the ice shelves were retreating just as Mercer predicted, the paradigm of the potential for rapid deglaciation of WAIS seemed to be in decline. No strong observational evidence for current retreat was forthcoming from the field programmes in West Antarctica, the models suggested that stability of a marine ice sheet was possible after all, and there was a lack of a plausible connection between ice sheet collapse and anthropogenic climate change. Finally, although the climate records from the Antarctic Peninsula show warming, there were (and still are) no direct observations to show contemporary climate warming over the larger part of WAIS (Vaughan et al. 2003).

Reflecting this declining paradigm, the Intergovernmental Panel on Climate Change, Third Assessment Review (Church et al. 2001), which was begun in the late-1990s but was not finally published until 2001, concluded that collapse of WAIS was unlikely, and would only result from ongoing response to long-term (Holocene) climate change, or conceivably from internal ice sheet dynamics (MacAyeal 1993). The assessment was that Antarctica was currently making little or no contribution to sea-level rise, and would continue to make little contribution over the next hundred years, with the dominant effect across Antarctica being that increasing rates of snowfall would slowly thicken the ice sheet and diminish sea-level rise from other sources.

## 7 Remote sensing observations of the 1990s and 2000s

But even as the IPCC was deliberating, a new eye was being cast over the unvisited and neglected portion of WAIS – the Amundsen Sea embayment. Prior to this time, satellites obtained only limited coverage of the more northerly parts of the Antarctic, and were limited to cloud-free daytime (summer) observations – data from the Amundsen Sea embayment were too few to detect any change in the ice sheet. This changed with the 1991 launch of the single most effective tool ever devised for detecting glacial change. The ERS-1 satellite carried two radar instruments, an altimeter and a synthetic aperture radar, each capable of observing the ice-sheet through cloud cover and throughout the Antarctic night and as far south as 81° S.

A team led by University College London analysed 5 years of ERS-1 altimeter seeking evidence of on-going elevation change (Wingham et al. 1998). They produced a map of thickness change covering a little over 50% of the continental area, and showed that over the large majority of the Antarctic ice sheet, no coherent change was measurable. In other words, over most of the Antarctic ice sheet the negative-feedback processes that act to keep the ice sheet in balance seemed to be operating well and, at least over this short period, no big imbalance, or contribution to sea level change, was detected. In one area however, in the Amundsen Sea embayment (primarily Pine Island and Thwaites glacier basins), there was an indication of surface lowering, at rates of more than 10 cm per year. Since these data covered only 5 years, and the change was in an area known to have very high rates of snowfall, the team was not confident to assign this effect to a dynamic change. It was still possible that the change represented a period of anomalously low snowfall. Despite their reticence, the inference was clear, that this portion of WAIS could be acting differently to the rest of the continent.

About the same time, the interferometric capability of the ERS-1 SAR was shown to capable of locating the region of tidal flexing in the ice sheet associated with the grounding line. Rignot (1998) showed that, over the period 1992–1998, part of the grounding line of Pine Island Glacier was retreating inland at a rate of almost 1 km per year. It was already clear that the ocean beneath Pine Island Glacier was capable of causing high rates of melt (Jacobs et al. 1996b; Jenkins et al. 1997), but these new results suggested excess melting was leading to ongoing thinning rates at the grounding line of $3.5 \pm 0.9$ m $\text{annum}^{-1}$, with the clear implication that these might have their origins in the ocean (Rignot 1998).

Interest in the Amundsen Sea sector was stimulated and a raft of other satellite studies followed. Analysis of repeat interferometry and sequential Landsat imagery (Rignot et al. 2002; Joughin et al. 2003) revealed two episodes of acceleration (1974–1987 and 1994–2000), separated by around 7 years of steady flow. Together these episodes increased the velocity of Pine Island Glacier by 22%. The acceleration was confirmed by observations of using visible imagery (Rabus and Lang 2003). Neighbouring Thwaites Glacier, in contrast, appeared to have a constant velocity but was widening into areas of previously stagnant ice (Rignot et al. 2002).

Bindschadler (2002) went back to the few useful visible images that were available for Pine Island Glacier. He showed that the floating portion of the glacier, its ice shelf, had in one part been thinning for almost three decades, perhaps at a rate of 4.8 m annum$^{-1}$, even though the frontal position of the ice shelf has not shown any clear trend over the last 50 years (Rignot 2002).

Shepherd et al. (2001) revisited the ERS-1 altimetry and found that the thinning of the grounded part of Pine Island Glacier was limited to the most rapidly moving parts of the glacier within 100 km of the grounding line – clear evidence that the effect is not simply due to unusual snowfall, but has its origin in a dynamic change. Thinning rates of the glacier near the grounding line were again confirmed as around 3 m annum$^{-1}$. Later, Shepherd et al. (2002) showed that same pattern was reflected across, not only Pine Island and Thwaites glaciers, but also on their smaller neighbours, Smith and Kohler glaciers. The widespread nature of the change, together with the evidence that the ice shelves throughout the region are thinning, was taken as evidence that the change is probably the result of excess melting in the ocean (Shepherd et al. 2004).

Subsequently, it became clear that the inland basins feeding ice to these glaciers were also thinning, albeit at a low rate but one which suggested that they were responding to the changes at the grounding line (Payne et al. 2004). It now appears that total measured acceleration of the glacier, is sufficient to explain the thinning and imbalance of the basin (Rignot et al. 2004b), which hints at the possibility that prior to the recent acceleration the glacier was close to equilibrium. If this is true, then the potential for changes to propagate inland into the heart of an ice sheet may be more rapid, and the sensitivity of the system higher, than would have been expected even 10 years ago.

Most recently, a study, similar to that presented by Wingham, but using 12 years of satellite altimetry showed that much of the East Antarctic ice sheet was thickening at a slow rate, but also confirmed that the Amundsen Sea Embayment of WAIS has continued to thin, at rates matched only by a few small regions of the East Antarctic ice sheet (Davis et al. 2005).

Finally, although the retreat of ice shelves on the Antarctic Peninsula is not a direct parallel to the ice shelves around WAIS, one aspect of change on the Antarctic Peninsula seemed to indicate that Mercer's reasoning was sound. The loss of ice shelves on the Antarctic Peninsula has been followed by many-fold increases in the velocity of the glaciers that fed them (Rott et al. 2002; Rignot et al. 2004a; Scambos et al. 2004) and in considerable thinning of these glaciers (De Angelis and Skvarca 2003; Scambos et al. 2004). Given the very different geometry (seaward-sloping bed) of these glaciers compared to WAIS ice streams, it is arguable how relevant these results are, but similar acceleration and thinning of Jacobshavns Isbrae in Greenland in response to shrinkage of its floating tongue (Thomas 2004) undoubtedly add to our confidence that the removal of ice shelves will cause glacier-flow to accelerate.

## 8 The return of the paradigm?

In less than a decade, we have become more certain that there is a dynamic connection between the extent floating ice shelves and the glaciers that feed them, and observational studies have shown us a bewildering pattern of ice-sheet change across much of the Amundsen Sea sector of WAIS. Indeed, all of the elements of the positive-feedback cycle that would, according to Mercer, lead inexorably to collapse, have now been observed on Pine Island Glacier: thinning of the ice shelf, inland migration of the grounding line, acceleration of the main trunk of the glacier, and thinning rates on the interior basins. In short, if 30 years ago Mercer and his colleagues had described the changes they would have expected as diagnostic of emergent collapse, this is the list that they might have written. Furthermore, the recently observed changes are occurring in the area of WAIS – precisely the area considered to be most vulnerable to collapse. Mercer himself noted that unlike, the Weddell and Ross sea sectors which drain through ~500-km wide ice shelves, the Amundsen Sea sector has only narrow ice shelves that might provide less buffering against collapse. Also, the Amundsen Sea sector rests on a deep bed and comparatively little thinning would be required cause widespread floating of previously grounded ice sheet. The Amundsen Sea sector was, perhaps over-dramatically, described by Hughes (1981), as "the weak underbelly of West Antarctica". At least from the presently available observational evidence, an emergent collapse of this portion of WAIS seems distinctly more likely, than it did just 5 years ago when IPCC began their last (the third) assessment.

It should be remembered that in sea-level rise terms, the magnitude of the present changes are only modest. The current imbalance across the entire Amundsen Sea embayment is $51 \pm 9\ \text{km}^3$ of ice per year,[2] equivalent to only 1.3 cm of global sea-level rise per century (Shepherd et al. 2002).[3] This should be viewed against predictions of total sea-level rise of 20–90 cm (Church et al. 2001) in the next 100 years arising largely from non-Antarctic sources. If the present changes really are the emergent stages of the collapse, then there is a threat that these changes will accelerate and causing accelerating sea-level rise.

Observational evidence has progressed rapidly in the last few years, and it is arguable that the models have not kept pace. We are still a long way off being able to use these observations to make reliable, even defensible, simulations of the processes of grounding line retreat which might lead to collapse (Vieli and Payne 2005), and there is still uncertainty over what drives deglaciation of marine ice sheets (Hindmarsh and Le Meur 2001), or whether the grounding line of a marine ice sheet can exist in a stable, or at least neutral, position (Hindmarsh 2006). However, the dynamic connection between ice shelves and ice streams is becoming clearer (e.g., Schmeltz et al. 2002; Dupont and Alley 2005), as is the potential stability of the grounding line to perturbations at the grounding line (e.g. Hindmarsh 2006),[4] and the rate at which we can expect propagation of glacier thinning to progress inland (Payne et al. 2004).

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[2] Others have claimed a larger contribution (Thomas et al. 2004); but that assessment was made over a shorter time period and rested heavily on flux calculation and thus may not be as robust as the assessment from satellite altimetry.

[3] The most recent satellite assessments of imbalance in the Amundsen Sea embayment, indicate that the rate of loss may have tripled since this study was completed (e.g., Rignot 2008).

[4] Recently, several important studies, which have wide support within the ice-sheet modelling community, have been published. These studies argue, once again, that marine ice-sheet margins are inherently unstable (see, Schoof 2007a, b).

Also beyond our current understanding is the question of whether the hypothesized positive-feedback cycle would ever really be strong enough to grow unchecked? Or whether, there are inherent brakes in the system that could halt the feedback long enough for equilibrium to be re-established. One obvious brake could be hiding beneath the ice sheet. The positive feedback of grounding line retreat would be strong, only where the bed beneath a retreating grounding line dips inland, a substantial bedrock bump might halt retreat long enough to allow equilibrium to be regained. The fact that some Antarctic ice streams currently have grounding lines that are pinned on bedrock bumps (e.g. Rutford Ice Stream, Doake et al. 2001) seems to confirm the importance of this effect, but until recently only a handful of measurements of ice thickness were available from the Amundsen Sea sector and it was not possible to evaluate the potential for the topography of the bed beneath the glaciers to slow grounding line retreat. However, a collaborative venture by the US National Science Foundation and British Antarctic Survey in 2004/2005 collected more than 70,000 km of airborne geophysical data, which will allow mapping of the sub-ice-sheet topography across most of the Amundsen Sea embayment (Holt et al. 2006; Vaughan et al. 2006), and should thus eventually allow more reliable projection of the future of this portion of WAIS. Furthermore, the success of this field campaign together with the success of other teams flying out a base on the southern tip of Chile (Thomas et al. 2004), has exploded the myth that fieldwork in the Amundsen Sea sector is impossible – it is likely that much new fieldwork will now be proposed for this area.

The IPCC Fourth Assessment Report, which is now being drafted,[5] will need to address quite different questions to the Third Assessment. Thanks to the ERS satellites, the question of whether or not WAIS is in balance is to some degree answered. The IPCC can start from clear observations that over the last decade some large parts of WAIS have been close to balance, with imbalances resulting in changes in surface elevation of only a few centimeters per year. The absence of a really gross imbalance in WAIS as a whole probably makes complete collapse (5-m rise in sea level) very unlikely on the 100–200 year timescales with which the IPCC is most concerned. On the other hand, we can now be sure that there exists a significant area thinning across the Amundsen Sea sector and this sector alone contains the potential to raise global sea level around 1.5 m, which should be sufficient reason for continued, perhaps increased, concern. Furthermore, the rapidity at which changes appear to be able to propagate up the ice streams means that the onset of a pronounced extra Antarctic contribution to sea-level rise could occur within a few decades of initiation.

The research priorities for this area have also changed (see also, Rapley 2006). We must now determine if the changes are accelerating, develop the currently over-simplistic theories of collapse to determine if collapse is really likely, and establish whether there are any brakes in the system that might halt progress to substantial deglaciation. Finally, we should work to put the changes in the Amundsen Sea sector into their correct context. The collapse of the Amundsen Sea sector of WAIS could soon (decades to centuries) become the dominant effect in determining the Antarctic contribution to sea-level rise, but for the moment there are other changes in Antarc-

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[5] The IPCC Fourth Assessment Report, is now completed and published, it does, indeed indicate a substantial revision of how the current and future ice-sheet contribution to sea-level change was assessed (see, IPCC 2007; and related volumes).

tica that we should not ignore: ice-sheet thickening in East Antarctica probably due to increased precipitation (Davis et al. 2005); increasing runoff (Vaughan 2006) and acceleration of ice-flow off the Antarctic Peninsula (Rignot et al. 2005); continuing long-term readjustment of the ice sheet to Holocene change (Stone et al. 2003); and readjustment of the ice sheet as a result of the switch-off of Ice Stream C (Joughin and Tulaczyk 2002). Each of these, contribute to the overall effect that Antarctica has current sea level change, and each could grow, or diminish, at a different rate in future decades and centuries (see, Alley et al. 2005, for a more complete review of predictions of the Antarctic contribution to sea-level rise over the coming 100 years).

## 9 Renewed connection to climate change?

The evidence that current changes in the Amundsen Sea embayment have their origin in the ocean, raises another ghost, a possible causal link between rapid deglaciation of WAIS and anthropogenic warming may not be entirely out of the question. It would be easy to overstate the case, and there are few measurements to go on, but there may be a plausible connection between anthropogenic climate change and ice sheet retreat. Around most of Antarctica the relatively warm Circumpolar Deep Water (CDW) remains beyond the continental shelf and does not come into contact with the ice sheet. Recent measurements have shown, however, that it does flood onto the continental shelf in the Amundsen Sea embayment, and coming into contact with the ice shelves is responsible for the high rates of basal melting seen in this area (Jacobs et al. 1996a; Jenkins et al. 1997; Hellmer et al. 1998). These observations, together with those showing ice-shelf thinning (Shepherd et al. 2004), lead us to conclude that it could be that increased ice-shelf melting is the most likely root cause of changes across the Amundsen Sea sector of WAIS. However, there is currently little oceanographic data to confirm that this is indeed the case, and the degree to which any incursion of CDW is new, or increasing, is not known. For now, it is reasonable only to suggest that it is possible that thinning of the ice shelf is a response to changes in the ocean that might have their root in climate change.

Similarly, whether such a change in ocean circulation is reversible, either on a short or long time-scale is not known at present. Indeed, the more we become convinced about the potential for the ice sheet to respond on short timescales, the more likely it is that the changes we are currently seeing in the sheet are reversible responses to short-timescale (~decadal) drivers with their root in natural variability, and not an irreversible response to a long-term (~centurial) anthropogenic change.

## 10 Conclusion

Supported by recent observations made from satellites, the paradigm of the threatened collapse of the West Antarctic Ice Sheet that had been in decline through the 1980s and 1990s, now appears to be re-emerging – albeit in a modified form. Since most of WAIS is not showing change, it now seems unlikely that complete collapse of WAIS, with the threat of a 5-m rise in sea level, is imminent in the coming few centuries. However, for the first time, we have strong observational evidence that the Amundsen Sea sector of WAIS is currently thinning as a result of glacier acceleration, and this appears to have been caused by changes in the floating ice shelf. If the current changes turn out to be the precursors of collapse of even a few glacier basins, the Amundsen Sea sector could begin making a significant contribution to sea-level rise within a few decades or centuries. A doubling of glacier flow speeds across the sector would cause an addition of 5 cm per century to sea-level rise, and if those glaciers were to reach speeds similar to Jacobshavn in Greenland, the contribution could be ~30 cm per century. This may not be as dramatic as the original threat of 5-m rise over an unspecified period, but is sufficient to significantly exacerbate the threat of sea-level rise to coastal communities around the world and so should be a continued cause for concern.

Looking further into the future, it is ironic that the single most important piece of data that would advance our understanding of the potential for WAIS collapse is buried beneath ice sheet itself. Ice cores show that in recent inter-glacials temperatures were higher than today (The EPICA Community 2004). If WAIS responded to past episodes of warming with rapid deglaciation, then the likelihood of a repeat performance in the face of anthropogenic climate change would be much higher. If WAIS survived warmer inter-glacials, we could be more confident in assuming present changes might be reversed and a new equilibrium found. A record of this past behaviour undoubtedly remains in the sediments beneath the ice sheet. Indeed, sediments retrieved from near the margin of WAIS show some evidence for a smaller ice sheet in recent interglacials (Scherer et al. 1998), but no similar data have been gathered from the interior of WAIS, where they are really needed. Recent advances in rapid drilling technology could make such investigations a serious proposition in the near future. It is now 50 years since the last International Polar Year which is really when the whole debate about WAIS began, perhaps, the forthcoming IPY in 2007–2009 will raise sufficient interest and support to make such an effort a possibility.

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