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POSITION ANALYSIS:

polar ice sheets
and climate
change:

GLOBAL IMPACTS



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Australian Antarctic Division



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Photo: cover Eric Woehler and this page Grant Dixon, Australian Antarctic Division.

Position Analysis: Polar ice sheets and climate change: global impacts.

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1. introduction

Change in the mass of freshwater locked up as ice in Antarctica and Greenland has the greatest potential to affect global sea level in a warming world.

Modern satellite techniques are providing increasingly accurate evidence that mass loss from the polar ice sheets is contributing to current sea-level rise. This loss is due to increased discharge of ice by the large glaciers draining the ice sheets as well as greater surface melting.

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007) estimated the maximum projected total sea-level rise from 1980–1999 to 2090–2099, excluding any accelerated ice discharge from polar ice sheets, as 0.59 metres. The IPCC AR4 also considered that a further 0.20 m of sea-level rise might occur over that interval from dynamic changes to ice flow increasing discharge from the ice sheets, and that even larger values could not be excluded. The processes that might cause this increase are not fully understood or adequately included in present ice sheet models. The extent of such an increase is probably the largest unknown in the projections of sea-level rise over the next century.

Since the IPCC AR4, there have been further observations of increasing ice flow, highlighting the potential for future dynamic changes in the ice sheets. In the absence of well validated models, a wide range of heuristic projections for the maximum 21st century sea-level rise have been advanced. Hansen (2007) suggested that 5 m of sea-level rise is not beyond question, although other researchers (Pfeffer *et al.* 2008) challenge this, while Alley *et al.* (2008) comment on a worrying lack of agreement among these projections.

Sea-level rise, with associated effects such as increased frequency of severe storm surges, will be one of the greatest impacts of a warming world on human societies. Even if global warming stabilises, the ice sheets will continue to add to sea level for many centuries into the future. The melting of ice sheets also freshens the ocean water, with consequent impacts on ocean circulation (and hence global climate), marine environments, and the rate at which the ocean absorbs greenhouse gases such as carbon dioxide from the atmosphere.

The aim of this paper is threefold:

1. To outline the likely effect of global warming on the polar ice sheets, and the potential impacts of ice sheet change on sea level;
2. To inform Australian governments of recent developments in scientific research into 'ice sheet mass balance'; and
3. To identify issues for consideration in policy development.



Photo: Wayne Papps, Australian Antarctic Division.

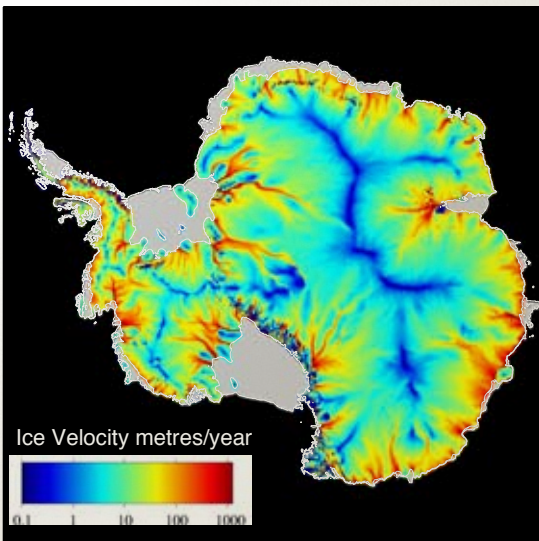
2. ice sheets and mass balance

The vast majority of ice on land is stored in the ice sheets of Antarctica (88%) and Greenland (11%). The total ice stored in the ice sheets is sufficient to raise global sea level by nearly 65 m.

Ice sheets in Greenland and Antarctica (Antarctica has separate East Antarctic and West Antarctic ice sheets) are immense and thick masses of ice that blanket the underlying land surface. Much of the ice in these ice sheets is over 2 km thick, and the thickest ice in East Antarctica is about 4.8 km thick.

Figure 1. ▼
Surface ice movement.

Surface ice movement (on a logarithmic scale) for Antarctica derived from a model for ice flow directions (Budd and Warner, 1996). This reproduces the observed faster ice flow nearer the coast and the focussing of the ice into fast moving streams. Floating ice shelves are shown as grey.



This volume of ice constitutes approximately 70% of all the freshwater on Earth.

The East Antarctic and Greenland ice sheets rest on bedrock that is mostly above sea level, but the ice in West Antarctica is grounded on a bed that is up to 2 km below sea level. The response of such a 'marine' ice sheet to external changes depends on sea level and ocean temperatures as well as on other climate factors, and it may be susceptible to rapid decay if the ice sheet thins and progressively begins to float.

Ice sheets are formed mainly from snowfall which, at temperatures that are typically well below the melting point, turns into ice over decades to centuries. Because the climate over the ice sheets is so cold, the air can hold only a small amount of moisture and the snowfall rates are very low. In the centre of Antarctica the annual snowfall represents less than 5 cm/yr of water, and the average over the total Antarctic ice sheet is only about 15 cm/yr. Nevertheless, because of the vast area of the ice sheet there is still a large annual addition of snow mass.

The ice sheets flow under their own weight, transferring mass from the interior towards the coast. There it is lost by the calving of icebergs into the ocean, by runoff of surface melt water (especially around the coast of Greenland) and by basal melting beneath the floating ice shelves which fringe much of Antarctica¹.

Ice motion occurs due to both internal deformation of the ice structure and by sliding of the ice sheet over the bed. In the high interior of the ice sheets, ice motion is very slow (only a few metres per year) and is mostly due to internal deformation. Nearer the coast ice flow accelerates (up to hundreds or even thousands of metres per year) and is often channelled into fast-moving ice streams. Antarctic ice streams and outlet glaciers typically feed into floating ice shelves which are major sites of final mass loss. The pattern of Antarctic ice flow is shown in Figure 1.

Ice shelves fringe 44% of the total Antarctic coastline, covering an area of 1.5 million km² with an average thickness of over 400 m. From time to time large icebergs calve from the front of the shelves where the ice has typically thinned to less than 250 m thickness.

¹ Ice shelves and icebergs are composed of fresh water. The other common but much thinner form of floating ice in polar regions is sea ice, which is formed by seasonal freezing of the ocean. Sea ice plays no significant role in sea level change and is not considered in this analysis. The role of sea ice in climate change is considered in a separate ACE CRC Position Analysis.

2. ice sheets and mass balance

Basal melting into the ocean below ice shelves can be as large as tens of metres per year beneath the thickest parts near the point where the ice first starts to float (called the grounding line).

Mass is continually added to an ice sheet by snowfall, and removed by melt and iceberg calving.

When the total mass of ice that is annually lost equals the annual mass gain, the ice sheet is said to be 'in balance'. Any imbalance between ice gain and loss results in a change in global sea level.

The loss of about 390 km³ of ice from the ice sheets (about 360 million Megalitre of fresh water, or 15 times the volume of water used by all Australian households and businesses in 2000–2001) will add 1 mm to global sea level.

Changes to the state of mass balance can occur with changes in the rate of snowfall or of surface melt (which may accompany climate change) or with changes in the rate of ice discharge (which can be due to causes other than immediate climate change). The amount and distribution of snowfall will respond quickly to changes in climate, but ice velocity over most of an ice sheet changes only very slowly, in response to changes in the ice sheet shape or temperature. However, large velocity changes may occur rapidly in ice streams and outlet glaciers in response to changing basal conditions or changes in the ice shelves into which they flow.

How is ice sheet balance measured?

There are two approaches to measuring the mass balance of an ice sheet – the integrated approach and the flux component approach (Jacka *et al.*, 2004).

In the **integrated approach**, direct estimations of the total change in mass or volume of the ice sheet are made over an entire ice sheet (or an individual ice drainage basin). This is usually done using satellite remote sensing technologies that have been developed over the last 15 years or less.

- Ice sheet surface elevation can be mapped using radar or laser altimeters on aircraft and satellites to measure the distance from the instrument to the surface, together with precise information on the location of the altimeter. Laser altimeter signals are more accurate and have a smaller surface footprint than radars, but they are unable to penetrate cloud cover. Knowledge of the density of the snow, and any changes to it, is also required to convert the altimeter height (volume) measurements into a mass change.
- Change of mass of the ice sheets directly affects the regional gravitational field, and ice sheet mass change has been estimated from satellite measurements of gravitational field changes (the Gravity Recovery and Climate Experiment (GRACE) satellite mission). The techniques used are sensitive enough to detect mass change from month to month, but some complicated corrections are required, and to date different analysis techniques give slightly different results.

The **flux component method** requires estimation of the difference between the sum of all the mass inputs to the ice sheet and the sum of all the outputs.

- Estimation of the mass input requires comprehensive knowledge of the spatially and temporally varying pattern of snow accumulation. In-situ observations generally only cover short periods and are sparse, with large areas of the vast ice sheets remaining unsurveyed. Accordingly, it is necessary to use other techniques, including satellite measurements of the microstructure of the snow which is related to the snowfall rate, to complete the map of snow accumulation. Recently, computer models of regional atmospheric circulation have been used to predict the snowfall patterns over the ice sheets (eg van de Berg *et al.*, 2006).
- Loss by summer melting of snow and ice in coastal regions, which is particularly important in Greenland, can also be well represented by melt and run-off models using results from meteorological models (eg Hanna *et al.*, 2008).
- Where the ice sheet flows into the ocean, there is a direct loss by ice discharge. This is conventionally estimated where the ice begins to float, since the ice discharge across this 'grounding line' directly contributes to sea level because at that point it displaces seawater². This requires observations of the speed of ice flow and the thickness of the column of moving ice. Satellite observations have been used to provide wide coverage of ice surface velocities. Ice thickness can be measured with airborne radar systems, or estimated from satellite measurements of surface elevation of floating ice just downstream of the grounding line.

² The ice downstream of the grounding line is already floating so its subsequent melting does not significantly affect sea-level rise, although it contributes to ocean freshening.

3. ice sheets and sea level

Imbalance in ice sheet mass: lessons from the past

The importance of ice sheets to sea level is seen from major ice sheet fluctuations in the past as revealed by ocean sediment and ice core records.

For about the last one million years, these fluctuations have been dominated by ice age cycles lasting around 100 thousand years, with sea level falling more than 100 m below today's levels during glacial times. The Earth has been in a high sea level/low-ice volume 'interglacial' climate, like the present 'Holocene' period, for about 10% of this time.

The glacial cycles are driven by small changes in the Earth's orbital geometry, causing subtle changes in the amount, distribution and timing of incoming solar radiation. These small effects are amplified by processes such as changes in the reflectivity of the ground when covered by ice or snow (albedo feedback), and alterations in the concentration of carbon dioxide (a greenhouse gas) in the atmosphere through interactions with the ocean and biosphere.

The last interglacial period (LIG) occurred around 125 thousand years ago. At the peak of the LIG global temperatures are thought to have been around 2°C warmer and sea level at least 4–6 m higher than their present values (Overpeck *et al.*, 2006). The bulk of that sea-level rise must have been from melting ice sheets in Greenland and Antarctica.

The rate of change of sea-level during the LIG is also relevant to what may happen in the future. LIG sea-level rise of 4–6 m or more above present values may have occurred gradually, or with abrupt steps as ice sheets collapsed due to rapid dynamic processes. Estimations based on marine sediment and coral data (Rohling *et al.*, 2008) show periods of sea-level rise at rates of 1.6 m per century during the LIG. These past natural changes indicate that similar rates of sea-level rise could result from human-induced warming. Semi-empirical projections of sea-level rise of over 1 m by 2100 cannot be ruled out (Rahmstorf, 2007; Pfeffer *et al.*, 2008).

Ice sheets and recent sea-level rise: conclusions from IPCC AR4

From 1850–1899 to 2001–2005, average global surface air temperature increased by 0.76°C (IPCC, 2007) leading to warming of the oceans and melting of ice on land. Church and White (2006) used a combination of tide-gauge records and more recent satellite-altimeter data to reconstruct global sea level from 1870 to 2004, showing a global average rise of 0.17 m during the 20th century.

Records also suggest an acceleration of sea-level rise from about zero rate of rise around 1820 to a rate of 1.8 mm/yr from 1961 to 2003, and 3.1 mm/yr over the period 1993–2003 (IPCC 2007; ACE CRC 2008).

The IPCC AR4 estimated that the two largest contributions to 20th century sea-level rise were ocean thermal expansion and the melting of glaciers and ice caps (excluding Greenland and Antarctic ice sheets).

Thermal expansion of ocean water is estimated to account for 0.4 mm/yr of sea-level rise for the period 1961–2003, increasing to 1.6 mm/yr during the last decade. Glaciers in most mountain regions are retreating. The contribution from ice caps and glaciers was 0.30–0.45 mm/yr sea-level rise over the last 100 years, rising to 0.80 mm/yr over the last decade (Dyurgerov and Meier, 2005).

Ice sheet losses and freshening of the global ocean

When ice sheets melt they add freshwater to the ocean, not only raising sea level but also decreasing ocean salinity. If all the ice on land were added to the oceans, it would decrease average ocean salinity by about 2%.

A large part of the heat transported by the oceans is carried by what is called the global thermohaline circulation (or global ocean conveyor). This part of the ocean circulation is driven by differences in sea water density which depend on temperature and salinity.

Changes to the salinity of the upper ocean could affect this circulation and have a serious and abrupt impact on global climate. The freshening could also impact marine ecosystems and, by increasing the stable stratification of the ocean, may alter the rate of uptake of carbon dioxide from the atmosphere.

3. ice sheets and sea level

The AR4 was also able, for the first time, to conclude that, taken together, the ice sheets in Greenland and Antarctica have very likely (>90% probability) been contributing to sea-level rise over the period 1993–2003 – at an average rate estimated at 0.4 mm/yr (or 4 cm/century). The IPCC AR4 concluded that there has been thickening of the high central ice sheet in Greenland, but this has been more than offset by increased melting and thinning near the coast. Flow speed has also increased for some Greenland outlet glaciers.

In Antarctica, mass loss has been greatest along coastal sectors of the Antarctic Peninsula and West Antarctica, but with thickening further inland and over most of East Antarctica partially offsetting this. Recent changes in ice flow rates observed in satellite data explain much of the estimated Antarctic mass imbalance. The IPCC AR4 assessment of all current contributions to sea-level rise is shown in Table 1.



Photo: Eric Woehler, Australian Antarctic Division.

Source	Sea-level rise equivalent (mm/yr)	
	1961–2003	1993–2003
Ocean thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic Ice Sheets	0.14 ± 0.41	0.21 ± 0.35
Total from all sources	1.1 ± 0.5	2.8 ± 0.7
SLR from observations	1.8 ± 0.5	3.1 ± 0.7
	(tide gauges)	(satellite altimetry)
Difference	0.7 ± 0.7	0.3 ± 1.0

Table 1. ◀
Contributions to the rate of sea-level rise estimated by IPCC AR4.

Source: IPCC, 2007

3. ice sheets and sea level

Ice sheets and present sea-level rise: advances since IPCC AR4

Since late 2005 – which was the cut-off date for research work assessed by the IPCC AR4 – a number of further studies of the ice mass budgets of Greenland and Antarctica have been made using satellite altimetry, satellite gravity measurements and estimates of mass influx and discharge from a variety of techniques. These confirm that both the Greenland and Antarctic ice sheets are losing ice mass and contributing to sea-level rise. The rate of loss from Greenland also appears to be increasing. A significant part of the losses is due to increased discharge of ice by large glaciers rather than by surface melt.

Antarctica

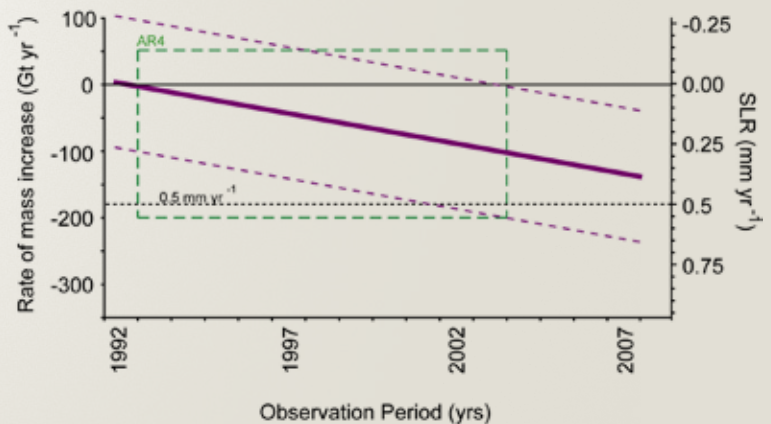
Recent studies of Antarctic mass balance, using both integrated and component methods (see box on page 5) strengthen the view that the ice sheet is losing mass to the ocean.

From satellite radar altimetry, Zwally *et al.* (2006) and Davis *et al.* (2005) estimated that over the period 1993–2003 there was a general pattern of East Antarctic thickening (mass gain) and West Antarctic thinning (mass loss). One possibility is that the East Antarctic change was due to increased snowfall, but Monaghan *et al.* (2006) found no evidence of systematic change in snowfall in a 50-year record derived from meteorological records and ice core data. Analyses of GRACE satellite gravity data between April 2002 and July 2005 (Velicogna and Wahr, 2006a) and between July 2002 and March 2005 (Ramillien *et al.*, 2006) show a similar pattern of near balance for East Antarctica, and mass loss from West Antarctica. The magnitude of the reported losses and gains was however somewhat different in these two gravity studies. In all of these studies, the West Antarctic loss was greater than any East Antarctic gain, and Antarctica as a whole was losing ice.

Rignot *et al.* (2008a) determined the ice discharge across 85% of Antarctic coastline from satellite radar interferometry measurements of the surface velocity of the ice and the ice thickness at the grounding line derived from surface elevation measurements of floating ice. Combining the resulting estimates of ice discharge with snowfall estimates from meteorological modelling (van de Berg *et al.*, 2006), they were able to apply the flux component method to individual Antarctic drainage basins. For the year 2000 the overall mass balance was almost zero for East Antarctica but with mass losses in West Antarctica and along the Antarctic Peninsula. The study showed that ice loss from West Antarctica was very large in the basins draining into the Bellingshausen and Amundsen Seas where glaciers have been previously observed to accelerate (Joughin *et al.*, 2003). The ice discharge in this region increased between 1996 and 2006, increasing the net mass loss over the period by 59%. In East Antarctica some small loss has been observed over the last 20 years from the Totten Glacier basin near Australia’s Casey station.

Figure 2. ▶
Schematic representation of the net mass balance of the Antarctic Ice Sheet since 1992.

The solid purple line approximates the mid-point of a number of different estimates made for different periods and using different techniques, and the dashed purple lines show the approximate error range in the estimates. The green box represents the estimate made by IPCC AR4 for the period 1993–2003, and its uncertainties. *Source: adapted and simplified from Allison et al., 2009.*



3. ice sheets and sea level

The Antarctic Peninsula region has experienced much greater warming than the continent as a whole – over 3°C in the past fifty years (Meredith and King 2005). This has led to widespread retreat (Cook *et al.* 2005) and acceleration (Pritchard and Vaughan, 2007) of glaciers reaching the sea around the Peninsula coastline.

Figure 2 shows the range of these recent estimates of the mass balance of Antarctica. The total annual loss from Antarctica is around 100 Gt/yr (equivalent to about 0.25 mm/yr sea-level rise)³, but the error range is large and the trend in this figure may not be statistically significant.

Greenland

A number of different analyses of GRACE satellite gravity data over the last few years (post-IPCC AR4) give a consistent picture of mass loss from the Greenland ice sheet, particularly for the southern region (Velicogna and Wahr, 2005; Velicogna and Wahr, 2006b; Ramillien *et al.*, 2006). The estimated magnitude of the loss varies substantially between these authors. The analysis technique used in these studies gives estimates averaged over very large regions of the ice sheet. Luthcke *et al.* (2006) used a different

technique with better spatial resolution to study changes in individual drainage basins and at different elevation ranges from GRACE satellite data for the period July 2003 to July 2005. They estimated a Greenland mass gain above 2000 m surface elevation and a mass loss below 2000 m, yielding a negative net balance overall. Again, most of the net mass loss occurred in drainage basins in the south of Greenland.

Wouters *et al.* (2008) analysed five years of GRACE observations at finer scale, showing considerable year-to-year variation in the mass balance, particularly in summer ice loss. Longer-term gravity data are needed to confirm any trends in the net loss.

In Greenland there is a pattern of near-coastal thinning of the ice sheet along fast-moving outlet glaciers which is partially, but not fully, compensated by thickening at higher elevations (Rignot and Kanagaratnam, 2006; Howat *et al.*, 2007). Howat *et al.* (2008) show that in southeast Greenland many smaller glaciers are also contributing to ice loss. Near coastal surface melt and run-off have increased significantly since 1960 in response to summer warming (more

than 1.5°C at coastal climate stations over the period 1991–2006), but total Greenland snowfall has also increased (Hanna *et al.*, 2008). A flux component analysis by Rignot *et al.* (2008b) indicates that Greenland was approximately in mass balance during the 1970s and 1980s, but since 1997 the ice sheet has been losing mass at an accelerating rate.

Figure 3 shows the range of recent estimates of the mass balance of the Greenland Ice Sheet and its change with time. These data indicate that over the last decade the mass loss from Greenland has averaged about 150 Gt/yr (0.4 mm/yr of sea-level rise). As with Antarctica, the error range of these estimates is large, but for Greenland there is evidence that the mass loss may be increasing rapidly, as all recent estimates exceed the AR4 values. It should be noted, however, that there can be large variability from year to year in the surface melt in Greenland. The short-term observed changes, from GRACE data in particular which are only available since 2003 may reflect this variability rather than a long-term trend.

³ A Gigatonne (Gt) is equivalent to a million Megalitres, or 1 cubic kilometre of fresh water

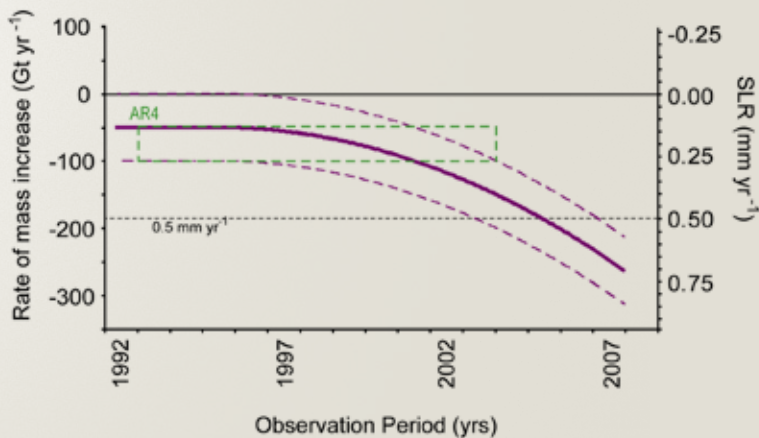


Figure 3. ◀
Schematic representation of the net mass balance of the Greenland Ice Sheet since 1992.

The solid purple line approximates the mid-point of a number of different estimates made for different periods and using different techniques, and the dashed purple lines show the approximate error range in the estimates. The green box is the estimate made by IPCC AR4 for 1993–2003. Source: adapted and simplified from Allison *et al.*, 2009.

3. ice sheets and sea level

Ice sheets and future sea-level rise: projections and unknowns

The IPCC AR4 made a suite of projections of future sea level change, corresponding to a wide range of possible scenarios for greenhouse gas emissions. These projections were derived from quantitative computer models based on the best available understanding of the physics of the climate system. The projections incorporate estimates of sea level contributions from ocean thermal expansion, glacier and ice cap melting, and changes in the Greenland and Antarctic ice sheets.

The IPCC AR4 projected sea-level rise by 2090–2099 in the range 0.18–0.59 m above 1980–1999 levels. These projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993–2003. While acknowledging that future ice discharge rates were uncertain, the IPCC AR4 suggested that, if ice sheet dynamic responses grew in proportion to global temperature change, there could be an additional 0.20 m of sea level by the end of the 21st Century (ie a total of 0.18–0.79 m).

The IPCC report added the significant caveat that because of the potential rapid dynamic change to ice sheets, sea-level rise larger than these projections could not be excluded.

As the IPCC AR4 noted, recent observations suggest that several facets of ice dynamics are not adequately represented in the current generation of ice sheet models and the impact of these is the largest unknown in making projections of sea-level rise over the next century.

The four main physical processes that the models used for the IPCC AR4 do not adequately treat are:

- the response of floating ice shelves to climate change;
- the connection between floating ice shelves and flow in the ice sheets;
- the nature of rapid flow in ice streams and outlet glaciers; and
- the effect of water at the base of the ice sheet on ice flow.

Antarctic ice shelves are vulnerable to both atmospheric and oceanic climate change. A number of ice shelves along the Antarctic Peninsula, where there has been pronounced regional atmospheric warming over the last 50 years, have decayed completely, sometimes collapsing in only a few months (Scambos *et al.*, 2003). Antarctic ice shelves can also be subject to high rates of ice loss from ocean driven basal melting, particularly near the grounding line, and therefore they are sensitive to ocean warming (Williams *et al.*, 2002).

Because ice shelves are already floating, they do not affect sea level significantly when they melt, but following the collapse of the Larsen B Ice Shelf, the outlet glaciers formerly flowing into this ice shelf accelerated by as much as eight-fold (Rignot *et al.*, 2004), draining more ice across the grounding line into the ocean and raising sea level.



Photo: K Steffen, University of Colorado.

3. ice sheets and sea level

These observations support the hypothesis that floating ice shelves can 'buttress' the flow of the ice sheet, and that the demise of ice shelves could lead to increased ice discharge at the grounding line. Many current ice sheet models do not properly treat the linkage of the ice shelves to the ice sheet.

For a marine ice sheet the linkage of floating ice shelves to the ice sheet is potentially of great importance. Thinning or ice shelf disintegration at the margin of a marine ice sheet, leading to accelerated flow in the grounded ice sheet, can thin the grounded ice and result in more ice starting to float. This ice is then also exposed to (relatively) warm ocean water, which can lead to further loss by basal melting. Wherever the bedrock is below sea level and deepens upstream, this process of thinning, faster flow and grounding line retreat can then progress into the ice sheet interior, with the potential for sustained sea-level rise.

Although the central parts of the Antarctic and Greenland ice sheets change only slowly, rapid changes have been observed over substantial areas near the coast where the influence of ice streams and outlet glaciers is felt. For example, the Pine Island Glacier in the Amundsen Sea sector of West Antarctica has accelerated 34% between 1996 and 2006, and it is now draining far more ice into the ocean than is gained upstream from snow accumulation (Rignot, 2008a).

Realistic modelling of such rapid flows and particularly the acceleration of outlet glaciers requires improved understanding of ice dynamics and better treatment of interaction between the ice and the underlying bedrock. This is particularly important in the case of Pine Island Glacier since it is a major outlet from the marine West Antarctic ice sheet, and observed accelerations here may already indicate the influence of warmer ocean waters.

Many of the outlet glaciers in southern Greenland have also increased their rate of flow significantly during the past decade or so. Summer surface melting has increased in Greenland and there is evidence that this melt water can make its way to the base of the ice sheet to lubricate ice sheet flow (Zwally *et al.*, 2002). These melt-driven processes are not well understood, but they potentially represent a mechanism by which climate warming could rapidly change ice sheet dynamics.

In Antarctica, surface melting is less prevalent, except along the Antarctic Peninsula where it has been implicated in ice shelf disintegration, but over 140 sub-glacial lakes have been detected at the base of the Antarctic ice sheet (Seigert *et al.*, 2005). Recent work has shown that these lakes are not necessarily static but undergo episodic drainage and refilling via sub-glacial rivers (Fricker *et al.*, 2007).

It is not clear how the water at the base of the ice sheet, in lakes, streams or saturated sediments, affects ice movement, or whether it signals a potential for greater sensitivity to changing conditions at the ice sheet margins such as ice shelf collapse.

Recent observations of increasing ice flow, and growing recognition of greater complexity of processes in ice sheet systems have led to concerns that the contribution of the Antarctic and Greenland ice sheets to sea-level rise over the 21st century could be considerably higher than the IPCC AR4 projections. Indeed, as discussed earlier, the IPCC AR4 considered that an additional 0.10–0.20 m of 21st century sea-level rise might arise if the discharge from ice sheets increased steadily with warmer temperatures. The IPCC AR4 warned that larger values could not be excluded and that understanding was too limited to provide a best estimate or an upper bound for sea-level rise.

Even in the absence of reliable models which capture these ice dynamic effects, several estimates of projected 21st century sea-level rise have been made. Rahmstorf (2007) suggested that total sea-level rise might have a simple dependence on the rising temperature, and suggested an increase of 0.50–1.40 m. Hansen (2007) has suggested that up to 5 m is not beyond question, although Pfeffer *et al.* (2008) argue that physical limits to ice sheet flow rule this out and they provide estimates of sea-level rise by 2100 in the range 0.8–2 m (using the IPCC AR4 projections of ocean thermal expansion).

4. science–policy issues

The single largest uncertainty in the IPCC AR4 sea-level rise projections for the 21st century is the dynamic response of the polar ice sheets to climate change.

Recent work also suggests that those sea-level rise projections themselves may prove too low. While scientists know that any acceleration in responses of the ice sheets will further increase sea-level rise, at present they are uncertain how large that contribution will be.

Indeed, the International Council for Science/WMO Joint Committee for the International Polar Year 2007–2008 statement on the State of Polar Research lists the contribution of the great ice sheets to sea-level rise and the role of sub-glacial environments in controlling ice sheet dynamics as research challenges of great urgency and societal relevance.

This large uncertainty in current projections of sea-level rise makes it difficult for policy-makers to put in place appropriate strategies and ensure adaptation resources are well directed. Australia's Antarctic research efforts will help to reduce the large uncertainty in sea-level rise projections associated with the polar ice sheets, providing policy-makers with narrower limits on projected sea-level rise, and enabling the development of more targeted and cost-effective adaptation policies.

Australian scientists have substantial expertise in modelling ice sheets and ice shelf–ocean interaction, in remote sensing and in field campaigns (for example on the Totten Glacier and Amery Ice Shelf in the Australian Antarctic Territory) vital to provide the data needed to improve our understanding of the dynamics of ice sheets.

The most efficient way to do this is by building on a record of collaborations with other nations.

Australia also has significant capacity for new field work through logistic support and increased access to the Australian Antarctic Territory using the Hobart–Casey Station air link.

The air link enhances Australian participation in international programs by providing air access to Antarctica. It also provides landing capability in East Antarctica for aircraft equipped for aerial geophysical survey which is crucial for advancing ice sheet science.

Addressing uncertainties related to the impact of changes to ice sheet mass balance on sea-level rise highlights the need for a comprehensive, interdisciplinary and integrated approach by policy-makers and scientists to ensure that the complexities and potential ramifications of such changes are fully understood. This can be achieved through the direct participation of scientists in deliberations about Australia's policy directions, while reducing the uncertainties requires the continued funding and resourcing of strategically focussed scientific programs.



Photo: K Steffen, University of Colorado.

5. conclusion



Recent estimates, using a variety of new satellite measurements, provide strong evidence that the ice sheets in Greenland and Antarctica are contributing more to present sea-level rise than was estimated by the IPCC AR4.

As the satellite time series lengthen, and as new space-based measurement systems are deployed, it will become increasingly clear how much, and from which regions of the ice sheets, loss is currently occurring.

The IPCC AR4 estimated a projected sea level rise over this century of between 0.18 m and 0.79 m. There is now emerging evidence that sea level rise by 2100 might exceed this.

It is important to recognise that although the IPCC AR4 projections focused on sea-level rise over the 21st century, in a warmer (even if stabilised) world, sea-level rise from ice sheets will continue for millennia.

Addressing the future response of ice sheets to global warming remains a major challenge. The next generation of ice sheet models will include better treatment of the interactions between ice sheets and ice shelves and account for any ice sheet acceleration when the buttressing effect of ice shelves is removed. Improved spatial resolution will give a better picture of the narrow fast flowing ice streams that drain much of the ice sheet. However, uncertainties about conditions at the base of the ice sheets and interactions with the surrounding ocean make it difficult to project accurately ice dynamic instability in response to changing climate.

Further investigation is needed to understand these processes, as well as the role of water beneath the grounded ice sheets.

Australia can contribute significantly to addressing the uncertainties identified in the IPCC AR4 report through maintaining and extending its scientific research into ice sheets by combining observational programs with modelling work.

The major dynamic ice sheet uncertainties are largely one-sided: they can lead to a faster rate of sea-level rise, but are unlikely to significantly slow the rate of rise. Semi-empirical projections suggest that sea-level rise of over 1 m is possible by 2100, and ice sheet analysis (Pfeffer *et al.*, 2008) suggests a maximum possible rise over this period of 2 m, with 0.8 m being a more probable value.

Recent observed sea-level rise has been near the upper end of the IPCC projections which include the ice sheet dynamic response (Rahmstorf *et al.*, 2007), and sea-level increase by the end of the century is likely to be well above the lowest end of the IPCC range.

Accelerated ice discharge has been observed in both Greenland and Antarctica. Although it is unlikely that total sea level rise by 2100 will be as high as 2 m, the probable upper limit of a contribution from the ice sheets remains uncertain.

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References

- Antarctic Climate & Ecosystems Cooperative Research Centre, 2008, *Position Analysis: Climate change, sea-level rise and extreme events: impacts and adaptation issues*. PA01.
- Alley, R. B., M. Fahnestock, and I. Joughin, 2008. Understanding glacier flow in changing times. *Science*, 322, 1061–1062.
- Allison, I., R. B. Alley, H.A. Fricker, R.H. Thomas, and R. C. Warner, 2009. Ice sheet mass balance and sea level. *Antarctic Science*. doi: 10.1017/S0954192009990137.
- Allison, I and 22 others, 2009. *The State of Polar Research. A Statement from the International Council for Science/World Meteorological Organization Joint Committee for the International Polar Year 2007–2008*. WMO, Geneva.
- Budd, W. F. and R. C. Warner, 1996. A computer scheme for rapid calculations of balance flux distributions. *Annals of Glaciology*, 23, 21–27.
- Church, J.A. and N.J. White, 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, 33, L01602, doi:10.1029/2005GL024826.
- Cook, A., A. J. Fox, D. G. Vaughan and J. G. Ferrigno, 2005. Retreating glacier-fronts on the Antarctic Peninsula over the last 50 years. *Science*, 22, 541–544.
- Davis, C. H., Y. Li, J. R. McConnell, M. M. Frey and E. Hanna, 2005. Snowfall-driven growth in East Antarctic ice sheet mitigates recent sea-level rise. *Science*, 308, 1898–1901.
- Dyrugerov, M. and M. F. Meier, 2005. *Glaciers and the Changing Earth System: A 2004 Snapshot*. Occasional Paper 58, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO.
- Fricker, H. A., T. Scambos, R. Bindschadler and L. Padman, 2007. An active subglacial water system in West Antarctica mapped from space. *Science*, 315, 1544–1548.
- Hanna, E., P. Huybrechts, K. Steffen, J. Cappelen, R. Huff, C. Shuman, T. Irvine-Fynn, S. Wise and M. Griffiths, 2008. Increased runoff from melt from the Greenland Ice Sheet: a response to global warming. *Journal of Climate*, 21, 331–341.
- Hansen, J. E., 2007. Scientific reticence and sea-level rise. *Environmental Research Letters*, 2, doi: 10.1088/1748-9326/2/2/024002.
- Howat, I. M., I. Joughin and T. A. Scambos, 2007. Rapid changes in ice discharge from Greenland outlet glaciers. *Science*, 315, 1559–1561.
- Howat, I. M., B. E. Smith, I. Joughin and T. A. Scambos, 2008. Rates of southeast Greenland ice volume loss from combined ICESat and ASTER observations. *Geophysical Research Letters*, 35, L17505, doi:10.1029/2008GL034496.
- IPCC, 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (eds). Cambridge University Press.
- Jacka, T.H., and the ISMASS Committee, 2004. Recommendations for the collection and synthesis of Antarctic Ice Sheet mass balance data. *Global and Planetary Change*, 42, 1–15.
- Joughin I., E. Rignot, C.E. Rosanova, B.K. Lucchitta, J. Bohlander, 2003. Timing of recent accelerations of Pine Island Glacier, Antarctica. *Geophysical Research Letters*, 30, doi:10.1029/2003GL017609.
- Luthcke, S.B., H.J. Zwally, W. Abdalati, D.D. Rowlands, R.D. Ray, R.S. Nerem, F.G. Lemoine, J.J. McCarthy and D.S. Chinn, 2006. Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science*, 314, 1286–1289.
- Meredith, M. P., and J. C. King, 2005. Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophysical Research Letters*, 32, L19604, doi:10.1029/2005GL024042.
- Monaghan, A.J. and 15 others, 2006. Insignificant change in Antarctic snowfall since the International Geophysical Year. *Science*, 313, 827–831.

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- Overpeck, J. T., B. L. Otto-Bliesner, G. H. Miller, D. R. Muhs, R. B. Alley and J. T. Kiehl, 2006. Paleoclimatic evidence for future ice sheet instability and rapid sea-level rise. *Science*, 311, 1747–1750.
- Pfeffer, W. T., J. T. Harper and S. O’Neel, 2008. Kinematic constraints on glacier contributions to 21st-Century sea-level rise. *Science*, 321, 1340–1343.
- Pritchard, H. D., and D. G. Vaughan, 2007. Widespread acceleration of tidewater glaciers on the Antarctic Peninsula. *Journal of Geophysical Research*, 112, F03S29, doi:10.1029/2006JF000597.
- Ramillien, G., A. Lombard, A. Cazenave, E.R. Ivins, M. Llubes, F. Remy and R. Biancale, 2006. Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change*, 53, 198–208.
- Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, 315, 368–370.
- Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R.F. Keeling, D. Parker and R. C. J. Somerville, 2007. Recent climate observations compared to projections. *Science*, 316, 709.
- Rignot, E., G. Casassa, P. Gogineni, W. Krabill, A. Rivera and R. Thomas, 2004. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters*, 31, L18401, doi:10.1029/2004GL020697.
- Rignot, E., 2006. Changes in ice dynamics and mass balance of the Antarctic ice sheet. *Phil. Transactions of the Royal Society*, 364, 1637–1655.
- Rignot, E., J.E. Box, E. Burgess, E. Hanna, 2008b. Mass balance of the Greenland ice sheet from 1958 to 2007. *Geophysical Research Letters*, 35, L20502, doi:10.1029/2008GL035417.
- Rignot, E., and P. Kanagaratnam, 2006. Changes in the velocity structure of the Greenland Ice Sheet. *Science*, 311, 986–990.
- Rohling, E. J., K. Grant, Ch. Hemleben, M. Siddall, B.A.A. Hoogakker, M. Bolshaw and M. Kucera, 2008. High rates of sea-level rise during the last interglacial period. *Nature Geoscience*, 1, 38–42.
- Scambos, T., C. Hulbe and M. Fahnestock, 2003. Climate-induced ice shelf disintegration in the Antarctic Peninsula. In: *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives*, *Antarctic Research Series*, vol. 79, E. Domack et al. (eds), 79–92, AGU, Washington D. C.
- Siegert M.J., S. Carter, I. Tabacco, S. Popov and D. Blankenship, 2005. A revised inventory of Antarctic subglacial lakes. *Antarctic Science*, 17, 453–460.
- van de Berg, W.J., M.R. van den Broeke, C.H. Reijmer and E. van Meijgaard, 2006. Reassessment of the Antarctic surface mass balance using calibrated output of a regional atmospheric climate model. *Journal of Geophysical Research*, 111, D11104, doi:10.1029/2005JD006495.
- Velicogna, I. and J. Wahr, 2005. Greenland mass balance from GRACE. *Geophysical Research Letters*, 32, L18505, doi:10.1029/2005GL023955.
- Velicogna, I. and J. Wahr, 2006a. Measurements of time variable gravity show mass loss in Antarctica. *Science*, 311, 1754–1756.
- Velicogna, I. and J. Wahr, 2006b. Acceleration of Greenland ice mass loss in spring 2004. *Nature*, 443, 329–331.
- Williams, M.J.M., R. Warner and W. F. Budd, 2002. Sensitivity of the Amery Ice Shelf, Antarctica, to changes in the climate of the Southern Ocean. *Journal of Climate*, 15, 2740–2757.
- Wouters, B., D. Chambers and E. J. O. Schrama, 2008. GRACE observes small-scale mass loss in Greenland. *Geophysical Research Letters*, 35, L20501, doi:10.1029/2008GL034816.
- Zwally H.J., W. Abdalati, T. Herring, K. Larson, J. Saba and K. Steffen, 2002. Surface melt-induced acceleration of Greenland ice sheet flow. *Science*, 297, 218–222.
- Zwally, H.J., M.B. Giovinetto, J. Li, H.G. Cornejo, M.A. Beckley, A.C. Brenner, J.L. Saba and D. Yi, 2006. Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992-2002. *Journal of Glaciology*, 51, 509–527.

