Chapter 22

Ice Sheets: Indicators and Instruments of Climate Change

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1. INTRODUCTION

Ice sheets of Greenland and Antarctica are uniquely arresting and captivating features of the Earth's natural environment. The hyperbole attached to their description, their sheer size and remoteness from the normal lives of most of us, guarantees their iconic status, but the emerging understanding that ice sheets contain a threat, which cannot be fully evaluated mean, that they have become a central issue in the climate change debate. However, while global climate has undoubtedly warmed during the recent past, and human activity has been a major factor in this change, the role of ice sheets as indicators of climate change and as influential components in the planets climate engine, is a complex one (Fig. 1).

This chapter will discuss the position of the great ice sheets within the climate change debate, contrasting the differing risks posed to sea-level rise by the Greenland and Antarctic ice sheets as likely contributors to future sea-level rise, and how they may differently influence the wider debate on limiting greenhouse-gas emissions.

2. SEA-LEVEL AND ICE

Although there are regional differences due, in part, to local subsidence and emergence rates of coastal land, global sea level is rising. We see this rise both in the century-long record from tide gauges around the world, and in

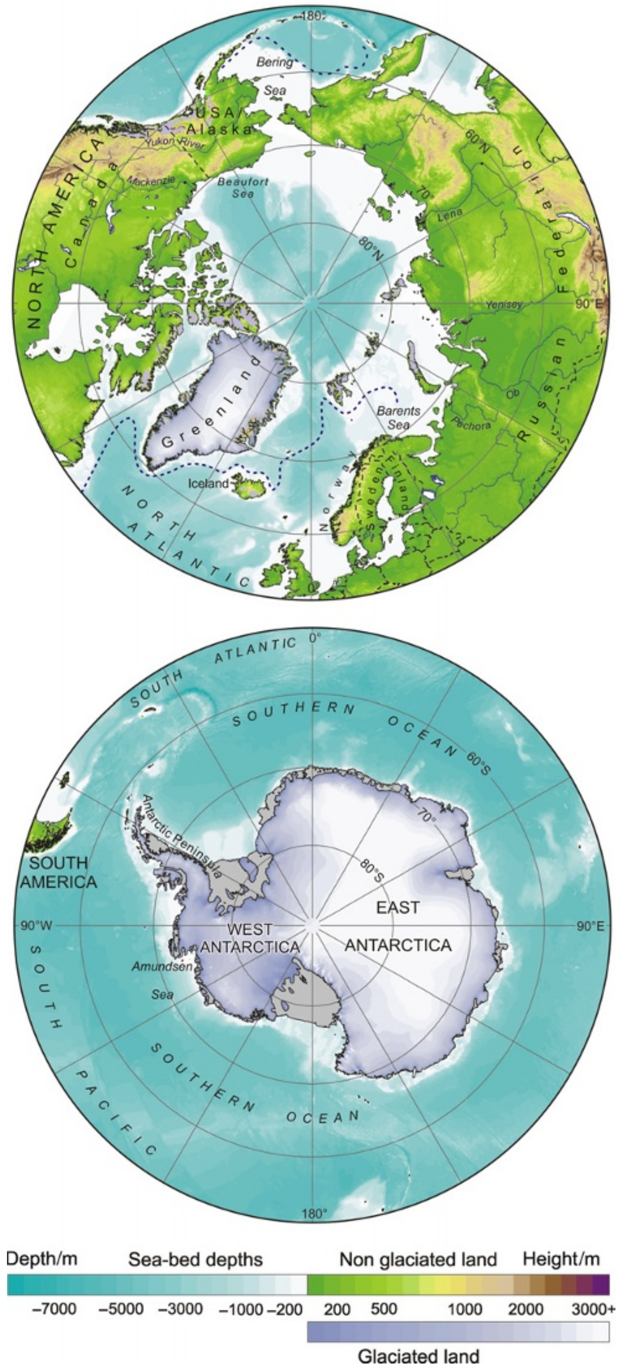

FIGURE 1 Maps of the north and south polar regions showing ice sheets and place names used in the text. Modified from Ref. [19].

the shorter record from satellite monitoring of the ocean surface elevation. In recent decades, the rate of global sea-level rise has been more than 3 mm/year. This rise is made up from various contributions: thermal expansion of ocean waters; changes in the mass of water contained in mountain glaciers, reservoirs and ground-water acquifers and changes in the ice-sheets of Antarctica and Greenland.

This rate of sea-level rise may not sound serious but unlike some other climate variables, sea-level tends to change smoothly, and the current rate of rise is likely to continue and most probably grow in the future. The cumulative sea-level rise over coming decades will have surprising and profound and impacts on coastal ecosystems, human populations and the stability of some economies. Climate change is very likely to accelerate most of the individual contributions to sea-level rise, and thus accelerate the rise in global sea-level. It is still not entirely clear that accelerating rates of sea level rise in the late twentieth century indicate that this acceleration has already begun [1], but there is very little doubt that sea-level rise will accelerate substantially during the twenty-first century.

The Fourth Assessment Review of the Intergovernmental Panel on Climate Change[1] (IPCC 4AR) [2] contains the most authoritative assessment and projection of sea-level rise so far undertaken. The review includes discussion of all the major contributors to sea-level rise, including, the contribution of the Antarctic and Greenland ice sheets. In summary, it predicts that by 2090–2099, sea-level will have risen 20–60 cm compared to 1980–1999. However, there are strong statements within the IPCC report that retain the possibility that the IPCC-4AR projections of sea-level rise maybe incomplete and potentially too conservative, and that the potential contribution from the ice sheets holds substantial uncertainty. These statements are most succinctly summarised in the Summary for Policymakers [3],

> *Models used to date [within the IPCC-4AR review] do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. The projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993 to 2003, but these flow rates could increase or decrease in the future. For example, if this contribution were to grow linearly with global average temperature change, the upper ranges of sea level rise for SRES scenarios shown in Table SPM.3 would increase by 0.1 to 0.2 m. Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise.*

The IPCC assessment has already been widely criticised by studies that range from the scientific [4] to those that are almost ideological in approach [5]. To fully understand the difficulties that the IPCC have faced, and the potential for

[1] The IPCC is a group of largely government-nominated specialists who are tasked with producing the most complete assessment of the science, impacts and potential responses to anthropogenic climate change.

resolution of this important question, we must first discuss the workings of the ice sheets, and the recent observations that have led the IPCC to be so cautious.

3. HOW ICE SHEETS WORK

To understand the influence that ice sheets have on the Earth system, it is important to have some insight into how an ice sheet, indeed any glacier, operates as a natural self-regulating entity.

Even during the warmest months, the inland parts of the Antarctic and Greenland ice sheets are too cold for significant melting of the snow surface to occur, and so, year-by-year, snow accumulates. If unchecked, this accumulation of snow would cause endless thickening, and in the absurd limit, this would drain the oceans of water. But snow eventually turns to ice, and this ice can, under great pressure, deform. Thus, within the ice sheets, ice is constantly moving, from the interior, into the glaciers and ice streams that take it back towards the coast. Eventually, ice re-enters the ocean either through iceberg calving, or though melting from the glacier surface or directly into the ocean.

The key mechanism that allows ice sheets to achieve apparently steady configurations is that glacial flow is driven by gravity and the driving force is proportional to the slope on the surface of the ice sheet. If snow accumulates more quickly than it is being removed by the ice flow, the ice sheet will get thicker, the surface slope from the interior to the coast will increase, and the rate of ice flow will increase – this will reverse the thickening. Thus the ice sheet has an inbuilt negative feedback, a system of self-regulation, which can produce equilibrium between accumulation and loss. In fact, the nonlinear mechanical properties of ice and its potential to slide over its bed, mean that even modest changes in the slope can have an enormous impact on ice-flow speed, and the ice sheet can be surprisingly quick to regain equilibrium after any disturbance.[2]

However, since the climatic variables that influence ice sheets are never entirely stable, no ice sheet is entirely in balance. Indeed, the geological records contain abundant evidence that ice-sheet configurations change dramatically with changing climate: twenty thousand years ago, around the Last Glacial Maximum (LGM), unbroken ice sheets covered vast land masses across the Earth. These ice sheets did not only cover enormous areas, they were also very thick, and they contained sufficient ice that global sea levels were some 120 m lower than they are today.

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[2] I am sometimes asked if the ice sheets will melt. And in answer, I am sometimes tempted to reply in positive terms, 'yes, all the ice in the ice sheets will eventually melt'. This would, of course, be unfair, without also noting that, so long as the ice that melts is balanced by new snow replacing it, the ice sheets will remain the same size. Although glib, this point explains why glaciologists refer to ice-sheet growth or retreat, and rarely use 'melt', so much favoured by journalists.

It took almost a hundred thousand years for the ice sheets to grow to this size, by the year-on-year addition of snowfall, but as climate warmed and melting took hold, it took little more than 15 000 years for most of the LGM ice sheets to melt, and for sea-level to rise. This asymmetry in rates of ice sheet loss and growth, is a feature of the geological record, and means that while global sea-level fall is only ever a rather sedate process, whereas sea-level rise can be comparitively rapid. Records from coral reefs show that the peak periods of ice-sheet retreat since the LGM, caused sea-level rise at rates of around 4 m/century.

Such rates of sea-level rise sound dramatic, even frightening, but just because such rates of change occurred in the past, should we expect similar rates in the future? Although several authors have used this analogue to infer the possibility of substantial rates of future sea-level rise [5], I believe that this is not a useful analogue for two reasons. Firstly, these estimates could be argued to be substantially too high because the highest rates of sea-level rise since the LGM occurred when there was vastly more ice in the world available to melt, and the total length of melting margin of those ice sheets was much longer. Secondly, these estimates could be argued to be too low, because those rates of sea-level rise occurred at times when climate change was many times slower than is predicted for the coming one or two centuries.[3] The fact that these are opposing, is no assurance that they will in any substantial way, 'cancel out'. A much better analogue for future conditions might be the last inter-glacial, for which there is emerging, but as yet equivocal, evidence for substantial rates of sea-level change. It is thus arguable that behaviour cannot be taken as a sufficient basis for predicting the future – we need to consider the ice sheets in much greater detail and predict their future on the basis of understanding their configuration and possible responses from a more mechanistic approach.

Today, there are two great ice sheets left on the planet, one on Greenland and the other on Antarctica. The Antarctic ice sheet is by far the larger covering an area similar to that of the contiguous states of the USA. By comparison, Greenland covers an area a little greater than that of Mexico. Trying to measure the degree of imbalance that exists in these ice sheets, has been a preoccupation of glaciologists for many decades, even before it was postulated that human activities were having an influence on climate, or that they could potentially also influence the ice sheets. These efforts were dogged by uncertainty for decades, until the late 1990s, when a new generation of satellites that could measure the volume, and flow or the ice sheets was launched.

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[3] The IPCC predicts global warming temperatures for the decade 2090–2099, that are 1.8–6.4 °C higher than 1980–1999; where the range expresses uncertainty due to the future emissions of greenhouse gases and uncertainty in model projections. This should be compared to the global temperature difference between glacial and interglacial conditions which is 4–7 °C, and this change took thousands of years to complete.

Since then assessment of the rates and patterns of change have become common and now show broad agreement [6,7].

Not only the area, but also the volume of ice contained in the ice sheets is substantially different. Antarctica contains sufficient ice to raise global sea level by 60 m, while loss of Greenland could raise it by around 7 m. However, these figures are to some extent misleading, since the risks associated with the Greenland and Antarctic ice sheets are closer in magnitude, but might be said to have a subtly different ‘flavour’.

The risk associated with the Greenland ice sheet can be characterised as the possibility that climate change will push Greenland into a state of imbalance, where it loses most of its ice (raising global sea-level by a little more than 5 m) over a period of several centuries to millennia. Because most of the Greenland ice sheet rests on rock that is close to, or above, current sea-level, for ice to be lost it must be transported to the sea by the glaciers. The rate at which this could occur is likely to be limited by the rate at which those glaciers could conceivably flow, and this is unlikely to be more than a few times the present rates. However, perhaps the absolute rate of loss is not the most significant point; lowering of the interior of the ice sheet would mean increasing areas of summer melt, once this process of retreat is fully underway, it would push the ice sheet as a whole further into imbalance, and the process of retreat could become self-sustaining. Continuing retreat would become inevitable and irreversible [8]. The critical threshold in atmospheric warming, that is required to begin this process could, if the higher projections of climate warming are to be believed, be exceeded by the end of the twenty-first century.

This argument frames the role of the Greenland ice sheet in the climate change debate. The hypothesis that human activities could push Greenland into a state where it continues to retreat for many centuries implies committing many, as yet unborn, generations to cope with the impacts of a rising sea-level that earlier generations have caused. Rightly, or wrongly, this has been used by many campaigners as a potent argument for early and vigorous reduction in greenhouse gas emissions to prevent this ‘tipping point’ being exceeded [9].

In contrast, large parts of the Antarctic ice sheet are considered to be relatively immune to rising atmospheric temperatures. Current climate is sufficiently cold that even under the most extreme projections year-round the ice sheet will remain frozen and generally unaffected. Indeed, for large parts of the East Antarctic ice sheet, the most likely impact of rising temperatures is an increase in snowfall rates. Perhaps, counter-intuitively, this may be a mechanism that slows the rate of future sea-level rise, although this should not be taken as a possible fix for the sea-level rise problem. Even if this hypothesis proves to be correct, its magnitude would probably reduce rates of sea-level rise by only 1 $mm \cdot a^{-1}$ [10]. Furthermore, a recent analysis of ice-core data from East Antarctica failed to show any evidence that increases in snowfall rates has yet begun [11]. The conclusion that the Antarctic ice sheet may be largely immune to atmospheric climate change,[4] certainly does not mean that it is insignificant in the sea-level rise debate. There is a part of the Antarctic ice sheet that is changing more rapidly than any other on the planet. The Amundsen Sea embayment of West Antarctica, is an area of ice sheet about the size of Texas, across which the ice sheet has been thinning for more than a decade at rates of a few centimetres per year on the interior to rates of several metres per year near the coast.

The Amundsen Sea embayment is a part of the West Antarctic ice sheet that has long been the focus of concern. 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 rests on a bed that is below sea level. Indeed, the bed topography beneath the ice is like a bowl, sloping down from the edge of ice sheet into a deep tectonic rift beneath its interior. If the ice sheet were removed, most of the area would be inundated by the sea. For this reason, those early glaciologists described WAIS as a "marine ice sheet", and they were quick to see a particular significance in this configuration. 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. With a bed below sea level, the ice sheet is anchored to its bed only because it is too thick to float. If areas around the margin of a marine ice sheet were to loose 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 has been frequently argued [13,14] that this could set up a positive-feedback cycle that would 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.

This idea, remained relatively dormant for many years, but has been recently reinvigorated by observations, that the ice sheet in the Amundsen Sea embayment, which has often been cited that the most vulnerable part of WAIS [15], is actually the area that is thinning most rapidly [16].

Furthermore, the thinning of the ice sheet in the Amundsen Sea embayment has been accompanied by indications that the some parts of the ice sheet are lifting away from their beds and beginning to float, which is another feature expected if a retreat of the type expected to result from the marine ice

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[4] This is not universally true, since a small part of Antarctica, the Antarctic Peninsula, has experienced very rapid recent rises in atmospheric temperature, and this does appear to be causing glacier and ice-sheet retreat in this area [12]. However, this area is only a small player in its contribution to sea-level rise.

sheet instability was beginning. Finally, it is now clear that the rate of ice loss from the Amundsen Sea embayment is accelerating, at a surprising rate. The loss from the ASE currently accounts for only 0.5 mm/year of global sea-level rise [17], but it does appear to be growing in an exponential way (around 1.3% per year).

The cause of these impressive, and concerning changes, is not yet entirely clear, but there is strong evidence that it arises from some change in the ocean surrounding the ice sheet – the Amundsen Sea itself. Essentially, it appears that the ocean is delivering more heat to the ice sheet than it once did, and that is melting and thinning the coastal margin of the ice sheet. Although it cannot be proved equivocally many researchers believe that this change in the ocean is has been driven by changes in the atmospheric circulation associated with greenhouse warming.[5]

To return to the comparison with Greenland, and the significance of these Antarctic changes to the policy debate; the fact that WAIS is a marine ice sheet means that, unlike the Greenland sheet, its response is not constrained by the speed at which its glaciers can deliver ice to the ocean. In effect, the sea could eat into the margin of the ice sheet and remove at whatever rate the ocean could remove the iceberg debris. Thus, the worst rates of sea level rise that could occur from WAIS are likely to be more rapid than that from Greenland. However, there is further complication, which is that current changes in the ASE, as mentioned earlier, are not likely to be due to changing atmospheric temperature, and making a clear attribution between ice-sheet change and anthropogenic influences on climate is significantly harder in Antarctica than it is for Greenland. Indeed, if there is proved to be an inherent instability in marine ice sheets, it may be argued that its retreat could be driven by a relatively small anthropogenic or natural variation. So, rapid sea-level rise from Antarctica could have a human, or a natural origin. Either way, the risks to unprotected coastal populations, and the cost of improving coastal defences to maintain protection, are the same, but the correct framing of the issues within the debate concerning reduction of greenhouse gas emissions is quite different.

4. SUMMARY

While we may debate the finer points of how climate change may interact with ice sheets, the general understanding that if our planet warms, ice sheets and glaciers will retreat and sea levels will rise, is not widely contested. It is clear from the geological records that this close connection between

[5] Essentially, their hypothesis is that increasing circulatory winds in the Southern Ocean draw more warm water onto the Antarctic continental shelf, and provide more heat for ice-sheet melting. However, a shortage of marine monitoring sites means that this is difficult to pin down with any real confidence.

temperature and sea-level has been maintained through many glacial cycles. And it is also clear that ice sheets contain the potential to raise sea-level at rates that are many times higher than those we have observed in recent decades. However, the overriding questions regarding the rate that ice sheets will contribute to sea level in coming centuries will remain unresolved until we attain a substantially improved understanding of ice sheet behaviour. The geological record of past changes is a guide in this regard, but today's ice sheets cannot be expected to respond to future anthropogenic change exactly as it did to past natural variations. The contrasting configurations of the Greenland and Antarctic ice sheets mean that they occupy subtly different positions within the climate change debate, both of which have been described as representing tipping points.

The way that the risk that ice sheets pose is perceived is an area that is also worth brief consideration. Studies of risk perception show that they many identifiable factors amplify the social importance and fear surrounding particular risks [18]. These include: the longevity of the risk; its apparent invisibility; and its potential to cause catastrophic events (rather than impacting a few individuals at any one time). As described in this chapter, each of these factors applies strongly to the threat of sea-level rise from ice sheet. Ice sheets may produce effects that, as with nuclear waste, many future generations will have to live with; they are so remote that they can be viewed as essentially invisible, and recent coastal flooding events, for example in New Orleans, have shown the huge scale and severity of the impacts that may become all the more frequent in future. All these factors may serve amplify the perception of the risk and to exert a powerful influence on the public and policymakers alike, but this does not mean that the risk does not exist, or can be ignored, and it is clear that a substantial number of scientists see sea-level rise as a worrying adjunct to the wider climate change debate, and an area where the scientific understanding that underpins predictions is particularly lacking.

We know immeasurably more about current changes in the ice sheets of Antarctica and Greenland, than we did even a decade ago, but it is arguable that this increase understanding has actually increased our uncertainty. Whereas the ice sheets could once be ignored as sleeping giants, there is now evidence they are becoming restless.

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