Global warming and the stability of the West Antarctic Ice Sheet

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Of today's great ice sheets, the West Antarctic Ice Sheet poses the most immediate threat of a large sea-level rise, owing to its potential instability. Complete release of its ice to the ocean would raise global mean sea level by four to six metres, causing major coastal flooding worldwide. Human-induced climate change may play a significant role in controlling the long-term stability of the West Antarctic Ice Sheet and in determining its contribution to sea-level change in the near future.

The West Antarctic Ice Sheet (WAIS) contains 3.8 million km^3 of ice. If this entire volume was released to the ocean, the time needed to restore the ice—at the present rate of accumulation—would be more than ten thousand years. The future of WAIS has drawn attention since Mercer[1] raised the spectre of its potential disintegration under the influence of anthropogenic climate change (global warming). In an early assessment of the global warming issue, Revelle noted, "The oceans would flood all existing port facilities and other low-lying coastal structures, extensive sections of heavily farmed and densely populated river deltas of the world, major portions of the states of Florida and Louisiana, and large areas of many of the world's major cities"[2,3]. Despite considerable progress in understanding certain aspects of WAIS in the interim, the 1995 report of the Intergovernmental Panel on Climate Change (IPCC) stated, "Our ignorance of the specific circumstances under which West Antarctica might collapse limits the ability to quantify the risk of such an event occurring, either in total or in part, in the next 100 to 1,000 years"[4].

With countries beginning to formulate global-warming policies, the potential hazard from WAIS is too large and irreversible to be relegated to a list of imponderables for consideration at a later date. Here I review our knowledge of WAIS from the perspective of global warming in the hope of clarifying key issues and highlighting the reasons for disagreement and uncertainty. The future of WAIS will be determined by internal responses of the ice sheet to millennia-scale trends in global climate and sea level, coupled with changes in the accumulation and discharge of ice due to global warming. The probability of a major contribution to global sea-level rise is low during the twenty-first century, but increases substantially thereafter. Atmospheric accumulation of greenhouse gases over the next 100 years could irreversibly affect the future of WAIS.

Two terms that are often used without definition are: "collapse", which I use here to mean the loss of most or all of the land-based (grounded) ice on a timescale that is much shorter than its accumulation turnover timescale[5]; and "unstable", which means that collapse of currently grounded ice would occur following small perturbations to its boundary conditions.

Physical setting

WAIS (Fig. 1) is a marine ice sheet, with part of its ice being grounded on land below sea level, and part in the form of floating extensions called ice shelves that move seaward but are confined horizontally by the rocky coast[6–10]. The boundary between grounded and floating ice is called the grounding line (Fig. 2). If the grounded ice were to melt, sea level would rise accordingly, by an amount proportional to the mass of grounded ice adjusted to account for the volume below sea level and for rebound of the bedrock (Fig. 2). Because ice shelves float, their melting would not displace additional water, and would not contribute to sea-level rise. Ice accumulates on WAIS through atmospheric precipitation and moves seaward from higher elevations under the influence of

gravity. Most of the drainage for WAIS is into the Ross and Weddell seas, where there are extensive ice shelves (the Ross Ice Shelf and the Filchner–Ronne Ice Shelf, respectively) and into the Amundsen Sea in the vicinity of Pine Island Bay, where extensive ice shelves are not present[11] (Fig. 1). If WAIS were instantaneously removed, West Antarctica would become an archipelago. Over a period of 5,000–10,000 years, the bedrock would rebound with removal of the ice load, but it would largely remain below sea level.

The stratigraphic record from the continental shelf around Antarctica indicates that WAIS began to form 15–20 million years ago[12,13], whereas analysis of deep-sea sediments suggests that it was about 9 million years ago[14]. Whether WAIS has been present continuously since that time is a matter of controversy[14–18]. There is ample evidence of repeated advance and retreat of the ice sheet, particularly from acoustic echo studies of the ocean floor, which bear the impressions of grounded ice in motion (for reviews of this evidence, see refs 7,19,20). Studies of marine sediment deposited on the continental shelf indicate that WAIS was considerably larger than its present size during the Last Glacial Maximum (LGM) 13,000–24,000 years ago[9], when the grounded ice extended at least several hundred kilometres beyond its current limit in the Ross Sea. Its ultimate limit is the edge of the continental shelf (Fig. 1) because it is nearly impossible to ground ice in the abyss[21].

The question of whether WAIS persisted through periods that were significantly warmer than the present interglacial period remains unresolved because of uncertainties in interpretation of proxy records for sea level, local temperature, and ice extent[9,22–24]. Based on evidence from lake sediments of a Pleistocene warm period in Antarctica, Mercer[1] surmised that WAIS may have completely disappeared at least once. Mercer also summarized evidence that global sea level stood at least 6 m higher during the last interglacial period about 120,000 years ago, but this high stand could not be tied directly to the poorly constrained chronology of the lake-sediment record. Nevertheless, these findings led to the inference that disintegration of WAIS may have caused sea level to rise at least once during a period when global mean temperature may not have reached more than 2 °C above that of today. Along with ideas, discussed below, that marine ice sheets may be inherently unstable, Mercer's findings led to concern that global warming might cause WAIS to collapse. In contrast, other major ice sheets either are largely grounded above sea level and subject to very gradual ablation from moderate warming (Greenland) or have no clear history of major, rapid, ice mass changes in the recent geological past (East Antarctica).

Ice gain and loss

The ice-sheet system gains mass through atmospheric precipitation over its entire surface and by freezing of ice on the underside of the ice shelves. It loses mass through evaporation, by melting and runoff at its surfaces (top, edges and bottom), and by calving of icebergs at the front of the ice shelves[25]. Ice may move across the grounding line
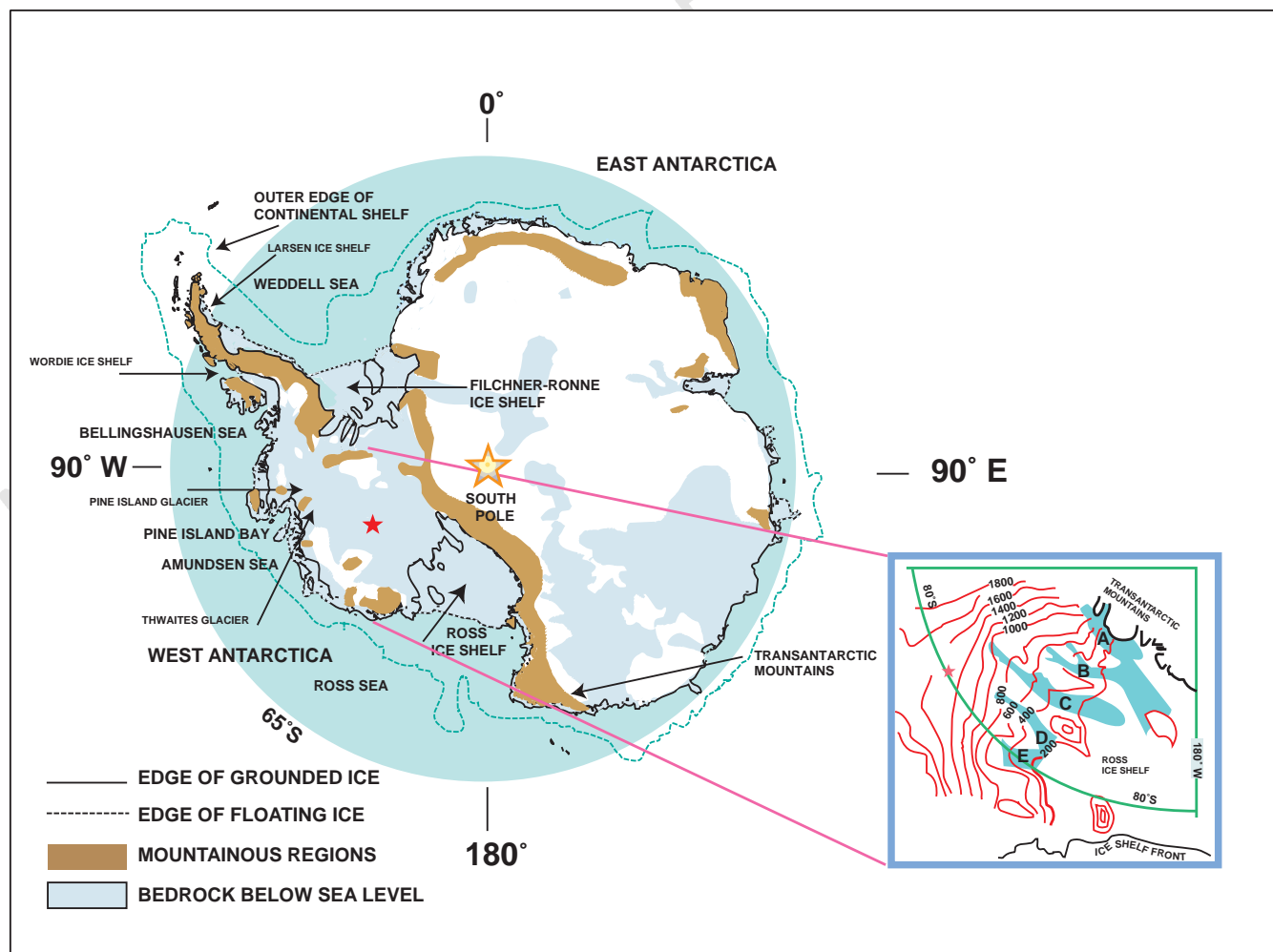
(which itself may shift in either direction), increasing or decreasing the mass of grounded ice[3,26,27]. Mass loss from the upper surface of the grounded ice by melting is currently negligible, and loss by melting from its base is estimated to be small[28]. Net flux of ice relative to the grounding line provides the only entry in the budget that could become large enough to account for significant net loss or gain of grounded ice, raising or lowering sea level.

The flow of ice from the grounded part of WAIS to the ocean is concentrated in fast-moving ice streams. About half of the ice flows into the Ross Ice Shelf (Fig. 1). The five ice streams in this drainage basin, each measuring 30–80 km wide and 300–500 km long, have been studied extensively using radar and photographic observation from aircraft and satellites, as well as Global Positioning and synthetic aperture radar satellite systems[29–32]. Subglacial properties have been studied using boreholes and seismic methods[6,33]. The ice in four of the streams is moving generally down a slope towards the grounding line at a speed averaging $\sim 0.5 \, \mathrm{km \, yr^{-1}}$, but with significant longitudinal (downstream) gradients. The ice streams move over sediments or bedrock and are separated from each other by ridges of relatively static ice (velocity $\sim 5 \, \mathrm{m \, yr^{-1}}$) of about the same thickness as the ice streams, but apparently in part frozen to their beds[7,34–36].

Ice streams were originally assumed to slide over bedrock, lubricated by meltwater from their base and restrained by frictional interactions at sites at the bed that are poorly lubricated. Seismic studies and evidence from boreholes and ocean-floor sediments prove that at least two of the ice streams move over a boundary layer of unconsolidated, water-saturated sediment up to several metres thick which lubricates their motion. This layer is proposed to be deformable till that is connected to the ice above. Movement of the ice is supposed to be controlled by deformation of the till, but the degree of control is a matter of dispute[37–42]. In an extreme view, ice streams move forward with minimal friction like a solid body floating on an inviscid fluid, in this way resembling ice shelves[21,43]. Reality is more complex because friction also arises from 'sticky spots' where the till is thin or absent and bedrock pinnacles contact the ice (and where lubrication by basal meltwater may play a role)[44]. Support of the ice-stream mass from the horizontal boundaries is also important[45]. The relative significance of each of these sources of flow restraint is uncertain and may vary greatly, both in space and time. For example, ice stream C (Fig. 1) nearly came to a complete stop in its lower reaches about 130 years ago, possibly owing to the diversion of basal meltwater to neighbouring ice stream B, which continues to move rapidly[46].

Ice streams also drain into the Filchner–Ronne Ice Shelf in the Weddell Sea[47–49] (Fig. 1) but these have not been as extensively characterized. A velocity of $0.4 \, \mathrm{km \, yr^{-1}}$ has been measured at the grounding line of one, the Rutford Ice Stream. The Thwaites and Pine Island Glaciers are the major ice streams draining into the Amundsen Sea (Fig. 1). The latter has a small ice shelf, and velocities of $1.3–1.9 \, \mathrm{km \, yr^{-1}}$ have been measured inland of the grounding line.

Figure 1 The Antarctic Ice Sheet (adapted from refs 2, 6, 101, 121). WAIS, located to the left of the Transantarctic Mountains, is largely grounded below sea level. Ice streams (A to E) draining into the Ross Ice Shelf are shown at lower right; ice elevation is in metres above sea level (adapted from refs 75 and 122). The red star in both maps, Byrd Station, is provided for orientation. WAIS as defined here includes the Ross and Filchner-Ronne ice shelves but not the Antarctic Peninsula (top left). The locations of mountainous regions, deep basins, margins of floating ice, and grounding lines at ice shelves are indicated approximately. The Transantarctic Mountains are divided in places by deep basins not shown here so that ice from both East and West Antarctica drains into the large ice shelves.

The Thwaites Glacier appears to have a floating but unconfined ice tongue. Neither ice stream is well characterized[11,50–53].

The motion of the Ross and Filchner–Ronne ice shelves is restricted by contact with rises on the ocean floor and by friction with the perimeter walls of the embayments. It has been argued that these obstructions, by pinning the ice shelf, exert backpressure or buttressing which prevents collapse of a marine ice sheet that otherwise would be unstable[27,54–57].

Two ice shelves fringing the Antarctic Peninsula to the north of WAIS, the Wordie Ice Shelf and the northern portion of the Larsen Ice Shelf, have been disintegrating for several decades, possibly because of local atmospheric warming[58–60]. They were not connected to major ice sheets, and their location is significantly warmer than that of the Ross and Filchner–Ronne ice shelves. The small Wordie Ice Shelf has lost about two-thirds of its area in the past thirty years, whereas the grounded ice behind it has not accelerated significantly[61]. But this observation may be irrelevant to the stability of a marine ice sheet like WAIS (should its ice shelves ever disintegrate) because the ice immediately behind the Wordie Ice Shelf is grounded largely at or above sea level.

Ice shelves close to the climate limit for existence ($\sim 0\,^{\circ}C$ in January, or $-5\,^{\circ}C$ mean annual isotherm) may be generally vulnerable to the rapid disintegration observed for the northern Larsen and Wordie ice shelves[59,60,62]. The relevance of such temperature thresholds to the much larger WAIS ice shelves is a key issue. The annual mean temperature on the ice shelves of West Antarctica is $-15\,^{\circ}C$ to $-25\,^{\circ}C$, and the mean summer value rises to about $-8\,^{\circ}C$ (ref. 63). A very large warming in summer, when widespread melting sometimes occurs on the ice shelves, could eventually cause them to break up and affect the stability of the grounded ice. Bentley[3] argued that melting due to the direct effect of a large atmospheric warming would take thousands of years, an assertion contested by Hughes[64] and called into question by the recent behaviour of the small ice shelves. In addition, recent studies indicate that significant basal melting already occurs under the large ice shelves. Changes in ocean circulation and temperature expected to accompany global warming could decrease basal melting at some locations[65] and increase it at others[28], the latter circumstance providing a potential pathway for thinning and disintegration of the large ice shelves even without a summer warming of $8\,^{\circ}C$.

Is WAIS unstable?

The question of stability[66–69] is important because the turnover time for WAIS is so long ($\sim 10^4$ yr) that a major contribution to sea-level rise over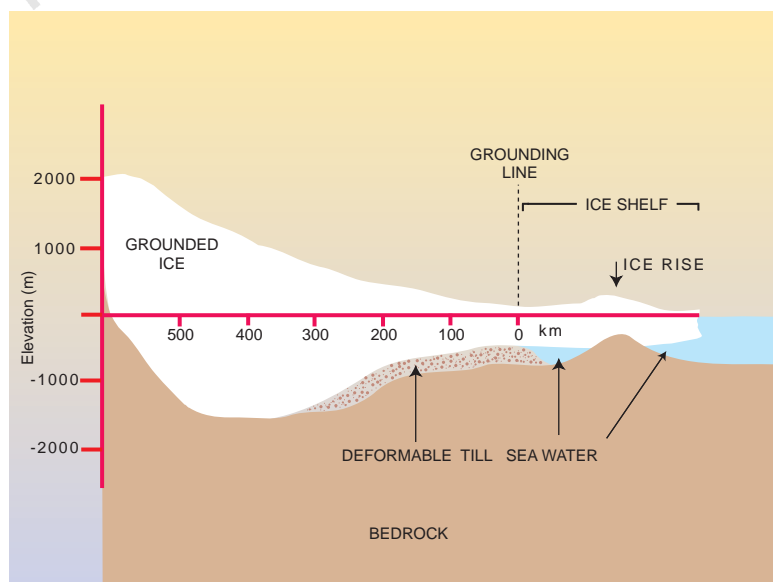 the coming centuries could not arise from a stable response to changes in the mass balance. Hughes[7,70] contrasted ice-stream profiles that are concave downward with early models of equilibrium ice sheets and also drew on stratigraphic studies in arguing that WAIS is inherently unstable and disintegrating as part of a regression from the LGM. Hughes also indicated mechanisms that could lead to very rapid grounding line retreat[7,64]. Others[3,27] have argued more convincingly that collapse could not occur within less than several hundred years.

The connections among ice geometry, velocity and instability have been emphasized in many studies[36,71,72]. But there is controversy over whether the fast and variable motion of ice streams is a symptom of instability[32,40,70] or a transient behaviour that may be damped short of collapse, or a permanent process that maintains a steady-state ice sheet by smoothly joining static inland ice with an ice shelf[3,40,73–75]. This question is likely to be resolved by determining the extent of basal lubrication, for example, deformable till.

Instability in the WAIS models. Weertman[26] provided a theoretical basis for the qualitative notion of very rapid grounding-line retreat in the absence of ice-shelf backpressure. Using a simplified model of the junction between grounded ice and a freely floating ice shelf, he demonstrated that if the bedrock slopes downwards in the inland direction away from the grounding line (a foredeepened profile, characteristic of several WAIS ice streams[29]), then a marine ice sheet may have no stable state. If an ice shelf providing buttressing becomes unpinned owing to melting or global sea-level rise, the grounded ice would accelerate its flow, thin, and rapidly float off its bed.

This hydrostatic instability is exacerbated when it appears in WAIS models that include a simple power-law relation between the ice velocity and the ice thickness at the grounding line[8,27]. Subsequent models use a more sophisticated (but not necessarily more realistic) description of the transition zone around the grounding line where stresses and velocities change from those typical of grounded ice to those characterizing an ice shelf[21,76–78]. These models have found steady-state solutions even with the ice shelves arbitrarily removed. However, it is unclear whether the newer approaches eliminate the instability generally, or whether stability arises from assumptions that need further validation. None of these studies incorporate ice streams bedded on deformable till.

Models that would incorporate such ice streams with underlying lubrication, in addition to more sophisticated descriptions of the transition zone, also may eliminate the hydrostatic instability of the grounding line. But a similarly problematic junction, where basal traction changes abruptly, occurs instead at the head (inland end) of the ice stream, where relatively static ice is joined to the fast-moving ice stream[21,79]. Describing the ice-velocity field around this junction

Figure 2 Cross-section of an ice stream and ice shelf of a marine ice sheet, indicating location of grounding line, bedrock rise on the ocean floor, and possible extent of deformable till. The thickness of the till layer, actually a few metres, is exaggerated for clarity. Sea-level rise due to collapse of WAIS was estimated by T. Hughes (personal communication) based on ref. 121.

has proved to be difficult, and simplifying assumptions can also lead to model instability (ref. 36 and discussion below), which may or may not be realistic. Furthermore, ice streams may be unstable with respect to horizontal accretion or loss of ice at their boundaries[80].

An additional problem is the wide range of timescales for the various processes that determine growth and shrinkage of an ice sheet. For WAIS, the characteristic time for restoring the ice sheet after total loss is 50,000 yr in one model[76] and for re-configuration of the bedrock in response to changes in the ice burden is 5,000–10,000 yr. The characteristic time for ice in the central part of WAIS to move to the grounding line is 1,200 yr (ref. 36) at today's velocities. Furthermore, the entire system experiences forcing by climate and sea level on all timescales. WAIS is necessarily in a continuing state of readjustment and never reaches equilibrium.

MacAyeal[81] elegantly demonstrated this point by incorporating ice stream dynamics and basal till explicitly into his ice-sheet model. The till layer is heated by friction and geothermal heat from below. It is effectively insulated from atmospheric changes by the overlying ice. A thermal–gravitational instability originates when the till changes from a frozen, consolidated phase to a deformable, dilated phase in response to changes in the basal temperature as the ice thickens. Because an ice sheet that has accumulated on a frozen bed is thicker than its equilibrium dimension on a deformable bed, the phase transition causes some or all of the ice to be discharged as icebergs[82,83]. The basal layer then refreezes and the cycle resumes with accumulation and thickening.

When this model is forced with periodic changes in climate and global sea level, deformable till develops and becomes widespread, and the ice sheet grows and discharges through ice streams on varying timescales. The magnitude and timing of the irregular and perhaps chaotic oscillations are affected by the changes in external boundary conditions, such as accumulation, that continually reset the internal clock of the ice sheet. Thus atmospheric changes influence the overall dynamics of the ice sheet by altering the transport of heat from and to the base, a process that has a very long characteristic time (of the order of 10^4 years). One curious feature of this model is that episodes of rapid discharge are not necessarily simultaneous with interglacial periods, and collapse may occur through different WAIS drainages at widely different times. Moreover, the model reaches a steady state (after about 50,000 years) if an instantaneous warming to today's climate is imposed on an initial state consistent with LGM conditions; this effect is due to ice-shelf buttressing.

So what can the models tell us about WAIS instability? We would need a more accurate model of an ice stream and its bed and far more measurements to decide whether WAIS is now within or approaching a rapid discharge phase. Models of the entire Antarctic Ice Sheet that do not incorporate ice streams[78,84,85] are informative but do not provide a sufficient basis for resolving the stability issue. The MacAyeal model gives important new insight into stability, but at a cost of using low resolution and limited descriptions of ice and basal layer thermodynamics and sub-ice topography. The descriptions of the ice-stream head, horizontal boundaries, and junction with the ice shelf require further development, and basal melting and freezing under the ice shelves is not taken into account. Models of individual ice streams also suffer many of these limitations.

The early idea[26] that WAIS is subject to hydrostatic instability and rapid grounding-line retreat seems unlikely, but this issue cannot be conclusively resolved without a better understanding of bedrock and grounding-line morphology, and ice-velocity fields, and improved models of the transition zone where the ice begins to float. The related question of how much the ice shelves influence the motion of the grounded ice remains undecided[76]. Many simulations, in models with and without ice streams/deformable till, show some effect on ice velocity of removing the ice shelves completely or imposing a rapid thinning upon them[27,43,76,86–89]. The observed seismicity beneath ice stream C (at a point 85 km upstream of the

Table 1 Empirical estimates of Antarctic Ice Sheet mass balance

	Accumulation on grounded ice	Accumulation total	Grounded ice balance	Total ice-sheet balance
Grounded ice* only	1,800 (ref. 92)		0 to +360 (ref. 92)	
	1,660 (ref. 93)		+40 to +400 (ref. 93)	
Total ice sheet†	1,528 (ref. 28)	2,144 (ref. 28)		−680 (ref. 94)

Estimates are given as Gt yr^{-1}.
* Adapted from ref. 4 (table 7.3).
† Includes accumulation on the Antarctic Peninsula and basal melting of the ice shelves.

grounding line and far outside the hypothetical transition zone) in response to tidal perturbations of the ice shelf provides direct evidence for an ice-shelf influence on the grounded ice far inland[90].

Propagation of changes in surface climate to the base of the grounded ice is very slow except near the grounding line. Thus the growth and discharge of WAIS has been partly programmed by the combination of internal dynamics and the slow response to past climate changes, for example those associated with Milankovitch cycles. In this model, WAIS may be destined to collapse over the next few centuries independent of anthropogenic climate change[91].

Is today's WAIS growing or shrinking?

Until recently, empirical studies argued for a positive (growing) mass balance for both WAIS and Antarctica as a whole[92,93]. In the absence of a validated model, this evidence provided support for the hypothesis of a stable WAIS[3,74]. The IPCC[4] estimated a zero Antarctic contribution to sea-level rise over the past century, and projected a small negative (about −1 cm) contribution for the twenty-first century. The latter estimate reflects a negative contribution to sea-level rise due to increased ice accumulation and an arbitrary, positive contribution (0.1–0.4 mm yr^{-1}) due to hypothetical WAIS instability. However, recent studies have inferred high melt rates under the floating ice, particularly in Pine Island Bay[25,28,53,94]. In combination with estimates of iceberg calving and runoff, these ablation terms exceed current values for net accumulation on the entire Antarctic ice sheet by 680 Gt yr^{-1} (Table 1), although a steady state lies within the uncertainty bounds[94].

After adjustment of the mass-balance estimates above[93] and the new melt rates[94] to account for drainage from WAIS only (S. Jacobs, personal communication), WAIS including ice shelves has a mass balance of about −280 Gt yr^{-1}. This estimate does not exclude a steady-state situation. Lower melt rates were recently inferred for the western sector of the Ronne Ice Shelf[95]. Assuming the lower values are characteristic of the entire Ronne Ice Shelf leads to a WAIS mass balance of −210 Gt yr^{-1}.

To estimate the implications of these mass-balance estimates for sea level, we assume that all the net ice-loss in the recent assessments[28,94] is from within the grounding line. The present Antarctic contribution to global sea-level rise would then be 1.9 mm yr^{-1}, of which 0.6–0.8 mm yr^{-1} would come from WAIS. These contributions would more than account for the difference between measured sea-level rise and model calculations of changes in ocean volume over the past century[4,25]. If unchanging, the projected increment to sea-level rise from Antarctica would be 19 cm over the coming century as compared to a total projected rise of 13–94 cm (ref. 4). The assumption that the entire negative ice balance corresponds to loss of grounded ice probably gives an upper limit, although it is conceivable that the ice shelves are gaining at the expense of the grounded ice.

Assessment of the mass balance for only grounded ice[92,93] yields a very different perspective (Table 1). Uncertainties are high because the mass balance is derived from differences between large and uncertain accumulation/loss estimates[34] and because direct velocity measurements for most of the inland ice of the Weddell sector do not exist. Nevertheless, the negative total ice-sheet mass balance can be reconciled with the positive grounded mass balance estimates

only if the ice shelves are undergoing unreasonably rapid shrinkage. These issues will not be resolved until accurate ice elevations become available from satellite-based laser altimetry.

This mass-balance analysis says little about the stability of WAIS beyond undercutting the argument that it is stable because it is not losing mass. Nevertheless, WAIS-average net discharge of grounded ice would need to increase by more than a factor of six to change the framework of the global sea-level rise problem as posed by IPCC (that is, to double the best estimate of ~50 cm rise over the coming century).

How rapidly could WAIS affect sea level?

I consider here the plausible upper limit on the rate at which ice can cross the grounding line, by focusing on discharge processes and, for the moment, ignoring accumulation. Several processes were thought to limit the rate of decrease of the mass of grounded ice even in situations where hydrostatic instability was assumed to apply[3,8,27]. Thomas et al.[27] estimated a minimum time of 400 years for disintegration of WAIS into the Ross Sea, with most of the ice loss occurring in the final century, after the ice shelf had melted as a result of a gradual warming of the ocean. Bentley[3] envisaged a 'parade' of ice passing through various 'exit gates' (that is, ice stream outlets, shelf fronts, and embayment narrows) which would need to be dissipated after crossing the grounding line to prevent thickening and regrounding of the shelf. He estimated a minimum time of 500 years for collapse of WAIS through Pine Island Bay, limited by the rate at which currents clear icebergs from the embayments where the glaciers terminate.

Currents in the Ross Sea and Pine Island Bay are higher than previously thought[28,94] and the 'parade' and 'exit gate' assumptions should also be reconsidered. Bindschadler[36] interprets the head of an ice stream as being an unstable junction that acts to accelerate static, upstream ice: it is assumed that the head marches backwards into the static ice rather than remaining fixed as others have implied[40,42]. Bindschadler[36] also assumes that the length of an ice stream remains constant. Interpretation of the profiles of ice streams B, D and E (Fig. 1) with this model leads to a prediction that the ice streams will drain the ice back to the centre of West Antarctica and the grounding line would then retreat at about the same speed. The balance of the ice eventually would flow laterally into the ice streams, or rapidly float off the bedrock once the ice streams are fully discharged. In other words, exit gates formed by ice ridges would collapse.

There is observational support for head regression on ice streams B and C[46], but it is unclear whether the head region is actually unstable[21,79]. Bindschadler[36] inferred a lower limit of 1,200 years for the remaining lifetime of WAIS, unless the apparent instability is damped. This lifetime corresponds to a mean contribution to sea-level rise of 30–50 cm per century. If this analysis were applicable to the fast-moving Thwaites and Pine Island glaciers, a collapse time of 500 years and sea-level contribution of 80–120 cm per century would be obtained.

For comparison, MacAyeal[81] obtains average rates of ice release equivalent to a sea-level rise of 25 cm per century during discharge episodes, corresponding to a collapse time of 1,600–2,400 yr. As ice shelves significantly retard discharge in this model (D. R. MacAyeal, personal communication), modelled discharge rates might increase if warmer conditions than those of the present interglacial were simulated, and if basal melting were taken into account.

Achieving a high rate of discharge (collapse timescale of 500 years) would require eventual collapse of the exit gates and, in the Ross and Weddell sectors, significant acceleration of the ice streams.

Global warming and WAIS

Climate change arising from anthropogenic activities[96] may influence the timescales of WAIS accumulation and discharge through modification of the state and behaviour of the atmosphere and ocean above and around Antarctica. So far, however, measurements are too sparse to enable the observed changes to be attributed to any such global warming.

An assessment of mostly coastal air-temperature data[97] shows a mixed pattern of modest warming and cooling (roughly $\pm 0.5\,°C$) when data for the period 1975–1994 are compared with those from 1955–1974. The Antarctic Peninsula shows a more substantial warming of ~1 °C over these periods and ~2.5 °C for 1945–1990 (ref. 98). Net annual accumulation of snow has increased at several locations in the interior of East Antarctica since 1955 (ref. 99). Histories of temperature and precipitation for longer periods have been inferred from ice cores at some locations but do not provide evidence of a uniform trend[100–102], except near the Antarctic Peninsula[103]. Some evidence of a negative trend in sea-ice extent has been presented[104], but the IPCC[97] assessment is that no trend has yet emerged, based on a two-decade times series beginning in 1973. However, indirect evidence of significant southward movement of the summer sea-ice edge in the two previous decades comes from examination of whaling records[105], and a small increase in sea-ice extent has been noted in satellite data since 1978 (ref. 106).

The effect of global warming on ice-sheet mass balance over the twenty-first century has been projected to be small and positive because it is generally assumed in ice-sheet models that the precipitation rate varies directly with the temperature-dependent saturation vapour pressure above the atmospheric inversion layer, resulting in additional accumulation[88,107,108]. Additional accumulation is also seen in GCM experiments[63,109]. Others have pointed out that precipitation trends also could be influenced by changes in storm patterns which cannot be projected accurately[110,111]. For atmospheric warming that extends over millenia or is very large (for example, more than about 8 °C locally), models of the entire Antarctic ice sheet show a negative mass balance due to dynamical effects and rapid melting[84,85,88,112]. However, these models do not capture changes in ice-shelf basal melting[28,65] that are likely to accompany changes in salinity, temperature and circulation in the circumpolar ocean arising from global warming over the next century, or the changes in ice-stream dynamics that may follow.

For example, increased precipitation would cause freshening of surface waters and reduced vertical convection and heat flux in the circumpolar ocean. Such changes would tend to decouple the surface and deep waters, causing the latter to warm. Results for the middle of the twenty-first century from the GFDL-coupled atmosphere–ocean general circulation model (AOGCM) forced with historical greenhouse gas and aerosol emissions and future emissions determined by the IPCC IS92a scenario[96,113] (R. Stouffer, personal communication) show a spatially variable pattern of temperature change at the sea surface around Antarctica, with some areas of modest warming (0–1 °C) and others of stronger cooling (0–2 °C) compared to a pre-industrial control run. But the picture is quite different at depth (295 m), where warming of 0.5–1.5 °C occurs generally and cooling is less (0–0.5 °C) and highly localized. At 755 m, near depths of the grounding lines for several of the ice streams, warming is slightly smaller but the pattern is similar. If greenhouse-gas emissions continue to increase at a rate similar to the IS92a scenario, warming could reach 3 °C at depths between a few hundred metres and one kilometre by year 2200 (ref. 114).

These results must be regarded with caution because the GFDL model has a relatively high sensitivity to doubling the atmospheric CO_2 concentration (3.7 °C) and no representation of ice shelves. Projections on the space scale of one of the ice shelves, or that of the cooler, downwelling areas, are beyond the limits of credibility of model resolution. The location and persistence of downwelling areas may be critical to determining changes in basal melt rates. Another transient simulation, with the Hadley Centre AOGCM[115] (J. F. B. Mitchell, personal communication), also projects zonal

mean warming at depth but this is smaller than the GFDL model for a given date, possibly because of the lower climate sensitivity of the former model. In these models, warming at depth goes hand-in-hand with the faster hydrological cycle that increases accumulation.

In today's climate, melting in Pine Island Bay is dominated by heat delivered by Circumpolar Deep Water (CDW), with water temperature already up to 3 °C above the *in situ* melting point. A 2-dimensional model simulation of the sub-ice circulation shows that the high melt rate could increase even further with subsurface ocean warming[116]. Based on the GCM results above, atmospheric warming and higher accumulation on Antarctica generally would be accompanied by higher basal melting at locations such as this one, where CDW dominates melting.

The Pine Island Glacier is roughly in mass balance at the present time[52]. The small ice shelf there, constrained only at its horizontal boundaries, may provide some buttressing. The Thwaites Glacier has no ice shelf to provide buttressing and its mass balance is unknown. The apparent stability of both ice steams may indicate that they are grounded on hypothetical bedrock sills[27,29,50] (or it could be taken as evidence against hydrostatic instability). Today's high melt rate beneath Pine Island Glacier ($\sim$10 m yr^{-1})[94], and the likelihood of even higher melt rates if CDW becomes warmer, raise the prospect that a sill eventually could be breached, exposing the deep subglacial basin behind it to sea water. The subsequent behaviour of these ice streams would depend on the reality of the hydrostatic instability.

Projecting the response to warming in the Ross and Weddell sectors is more complex because High Salinity Shelf Water (HSSW), formed at the sea surface freezing temperature as sea ice is produced, dominates melting today[28,48,86,117]. AOGCM simulations give contradictory forecasts on how global warming will affect sea ice and thus HSSW. If sea-ice cover and HSSW density increase, that should speed up circulation and moderately increase basal melting. If sea ice and HSSW formation decrease, basal melting may either increase or decrease, because less dense water on the continental shelves could allow more, and warmer, CDW to penetrate the sub-ice shelf cavities[118].

The melt rates of the Ross and Filchner–Ronne ice shelves are now estimated to be $\sim$0.22 m yr^{-1} and $\sim$0.55 m yr^{-1} or less, respectively. There is a range of plausible future melt rates, given the climate changes projected above, and the uncertainties in how HSSW and CDW will change[3,86,87]. For example, a basal melt rate of 2 m yr^{-1}, far lower than those inferred currently for the Pine Island Glacier, could remove half of the Ross Ice Shelf in a little more than a century[86]. Subsequently, the future of the grounded ice would depend upon the details of geology beneath the grounding line, whether hydrostatic instability is realistic, and whether the remaining shelf ice regrounds or disintegrates.

Changes in ice-shelf basal melting may also influence ice-stream dynamics in combination with thermal–gravitational instability[81]. Over several hundred years, surface warming cannot generally cause a phase change at the ice-stream bed. However, it is possible that the current configuration of WAIS is already unstable[36], or would be if the ice shelves disintegrated. Although Bentley[74] has argued that the frequency of unstable configurations is low ($\sim$0.001) if they occur randomly, episodes of rapid discharge appear to be correlated[81]. Regression from the LGM occurred relatively recently, and perhaps rapidly[7,9].

If we assume that WAIS is indeed in or near an unstable configuration, and that the world will continue to warm, then how may the rate of discharge change? First, thinning or removing the ice shelves may cause an increase of ice-stream velocities that would speed discharge by a factor of 2–3 (ref. 43). The higher velocities on the Pine Island Glacier and the Thwaites Glacier could be interpreted as supporting this proposition, although explanations apart from an absence of buttressing, such as higher basal shear stress, are at least as plausible. In addition, this velocity

increase would enhance frictional heating and extend the domain of lubricated basal conditions. We cannot assess the potential significance of the second process. But the first could presumably increase discharge into the Ross Sea by a factor of 2–3 (because absent hydrostatic instability, the rate of grounding-line retreat may be comparable to the ice-stream velocity), and shrink the collapse time to 400–600 years once discharge increases (based on ref. 36).

Future scenarios and policy implications

It is not possible to place high confidence in any specific prediction about the future of WAIS. Nevertheless, policy makers are confronted by three scenarios that span the range of plausible outcomes for WAIS, assuming continued growth in greenhouse-gas emissions according to rates characteristic of most of the IPCC 'IS92' emissions projections[96]. The following ice-sheet scenarios reflect the assumption that there is a gradual dynamic response to removal of the ice shelf, no dynamic response, and very rapid dynamic response, respectively.

(1) Ice streams remain active. Basal melt rates gradually increase, thinning and eventually eliminating the Ross Ice Shelf in 200 years. As the shelf thins, ice-stream velocities increase, leading to higher discharge rates. As a result, the Antarctic contribution to sea-level rise remains positive (0–19 cm per century), despite ice accumulation increases due to atmospheric warming. Eventually, static ice drains into the ice streams or floats. The duration of the collapse process is 500–700 years and the WAIS contribution to sea-level rise reaches $\sim$60–120 cm per century. Collapse might have occurred anyway, but more slowly, if the ice shelves had remained in place.

(2) Ice streams slow as a result of internal ice sheet readjustments. Discharge of grounded ice decreases even if the ice shelves thin. Velocities of the Thwaites and Pine Island glaciers do not change much because they are already moving fast. The Antarctic contribution to sea-level rise turns increasingly negative[88,119,120] until warming of about 8 °C has occurred, far more than expected over the next century.

(3) The Ross Ice Shelf thins and eventually disintegrates, and grounding lines recede rapidly owing to hydrostatic instability. The WAIS contribution to sea-level rise increases gradually over two centuries as the shelf thins and ice-stream velocities increase. Then sea level rises sharply as the bulk of WAIS is discharged in a matter of 50–200 years, perhaps limited by the speed at which embayments are cleared of floating ice. The whole process takes 250–400 years. WAIS also could discharge in the vicinity of Pine Island Bay by hydrostatic instability if one of the ice streams there is barely stable today: for example, resting on a sill. Given the clearing time of the embayment and inferred currents[3,94], the timescale would be about 200 years after melting destabilized the grounding line.

I assess the relative likelihood of scenario (1) to be highest of the three (but with low confidence), even though it would require considerable acceleration of ice discharge, because it best reflects the current activity of the ice streams and the probable mass balance of WAIS. Scenarios intermediate between (1) and (2) are conceivable, with lower sea-level rise than for (1): for example, if partial collapse is followed by readjustment. Progress on understanding WAIS over the past two decades has enabled us to lower the relative likelihood of scenario (3) but not to eliminate it entirely. One outcome that may be put aside for the moment, because no convincing model of it has been presented, is a sudden collapse that causes a 4–6 m sea-level rise within the coming century.

Scenario (1) would result in total rates of sea-level rise beyond year 2100 that are double or triple the median values projected by the IPCC for the twenty-first century. Global average rates of rise would exceed the recent historical value by about an order of magnitude and be comparable to today's effective rates in subsiding deltaic areas such as Bangladesh. Such rates of change pose a serious

challenge to societal adaptive capability and could prove devastating to coastal ecosystems.

Scenarios (1) and (3) would ultimately result in 4–6-m sea-level rise, accompanied by all the disruptive connotations noted by Revelle. Almost all sea-level rise would occur beyond the twenty-first century. However, these outcomes are predicated on changes in basal melt rates that could accompany global warming of only a few degrees, warming that could be determined by emissions that occur during the twenty-first century[96]. Given the long residence time of atmospheric carbon dioxide, and thermal inertia in the oceans, decisions being considered now could irreversibly affect WAIS in the distant future. For example, if global emissions follow any of several of the IPCC 'IS92' scenarios[96] over the twenty-first century, sufficient climate forcing may be created that, no matter what the policy responses are afterwards, substantial thinning of the Ross Ice Shelf during the twenty-second century would be assured. □

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