Rapid sea-level rise from a West Antarctic ice-sheet collapse: a short-term perspective

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ABSTRACT. Will worldwide sea level soon rise rapidly because of a shrinkage of the West Antarctic ice sheet (WAIS)? Here I give a personal perspective of that probability. The crucial question is not whether large changes in ice mass can occur, but how likely it is that a large, rapid change, say a several-fold increase in the 20th-century rate of about 2 mm a^{-1}, will occur in the next century or two from a West Antarctic cause.

Twenty years ago Weertman proposed that a marine ice sheet is inherently unstable. But Weertman's analysis was based on a simple model of a marine ice sheet that did not include fast-flowing, wet-based ice streams, which are now known to dominate the grounded ice sheet. Modern analyses do not definitively determine just how ice streams affect the stability of the WAIS, but it can at least be said that there is no compelling theoretical reason to expect a rapid rise in sea level from the WAIS triggered by ice-shelf thinning.

Of the three main ice-drainage systems in the WAIS, the one that flows into Pine Island Bay might be a particularly likely site for accelerated flow since there is no ice shelf to restrain the inflowing ice streams, yet measurements show that this system is not significantly out of mass balance. If the "Ross Embayment" system, which has undergone several sudden glacial reorganizations in the last thousand years, were unstable one might expect a history of large changes in the total outflow of ice into the Ross Ice Shelf, yet the total outflow in the "Ross Embayment" has remained relatively unchanged despite the large internal perturbations, a fact that points to a stable, not an unstable, system. Study of the third major drainage from the WAIS, into the Ronne Ice Shelf, also suggests that there is no gross discordance between the present velocity vectors and flow tracers in the ice shelf, although the evidence is limited.

In the light of the evidence for recent stability, it is difficult to see how climate warming (whether anthropogenic or natural) could trigger a collapse of the WAIS in the next century or two. Thus, I believe that a rapid rise in sea level in the next century or two from a West Antarctic cause could only occur if a natural (not induced) collapse of the WAIS were imminent. Based on a concept of pseudo-random collapse once per major glacial cycle, I estimate the chances of that to be on the order of one in a thousand.

1. INTRODUCTION

Will worldwide sea level soon rise rapidly because of a shrinkage of the Antarctic ice sheet? That is a question of widespread interest and great societal import; it is also a matter about which there is great uncertainty. A reader of reports in the popular press and of some documents promoting particular research agendas might conclude that such an event is likely and consequently that the coastal areas of the world are in imminent danger of inundation. In the Intergovernmental Panel on Climate Change Second Assessment Report, Warrick and others, (1996), after a brief but up-to-date review, stated that "estimating the likelihood of a collapse [of the West Antarctic ice sheet] during the next century is not yet possible". While I agree with that conclusion in a formal sense, I nevertheless believe that the relevant information at hand points strongly towards the unlikelihood of a collapse event in the next century or two. Here I give a personal perspective of present knowledge, arriving at an order-of-magnitude quantitative estimate of what I mean by "unlikelihood".

For the sake of quantitative discussion, I will define a "rapid" rise in sea level to be a rate of at least 1 m per century (10 mm a^{-1}), five times the 20th-century rate. (At the end of this paper I consider briefly a rise of twice the present rate.) A rate of 10 mm a^{-1} corresponds to an additional input to the ocean of 3000 km^3 of water per year, about one and a half times the total present-day outflow from the Antarctic ice sheet.

Glaciologists generally agree that a marine ice sheet, one that rests on a bed well below sea level, is much more likely to undergo a rapid change than one lying on a higher bed. Although there are sections of the East Antarctic ice sheet that are marine, I will focus on the West Antarctic ice sheet (WAIS) because it appears to be the most vulnerable, being open to the ocean on three sides, and because it comprises the bulk of the marine ice. If the entire WAIS were discharged into the ocean, sea level would rise by 5 or 6 m.

In fact, the WAIS surely has not been constant in size throughout the Pleistocene ice ages. Marine seismic studies show that it expanded across the continental shelf many times (Alonso, and others, 1992), whereas the subglacial occurrence of algal remains suggests that at other times the main WAIS inland ice was gone (Scherer, 1991). The crucial

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question in the present context, however, is not whether large changes in ice mass have occurred, but how rapidly they can occur and how likely is it that a large, rapid change will occur soon.

Like other large ice sheets, the WAIS is not a single dynamic entity; it comprises three major and several minor drainage systems that have separate regimens and are unlikely all to accelerate at once. But to consider the worst-case scenario, assume that the whole WAIS behaves as a unit. The WAIS produces about 320 $km^3\ a^{-1}$ (water equivalent) of ice outflow (Bentley and Giovinetto, 1991); thus, to achieve a sea-level-rise rate of 10 $mm\ a^{-1}$, a tenfold increase in the contribution of the WAIS would be needed. Approximately half of the WAIS is below sea level and consequently already displaces ocean water. Consequently, there are two conceptual end-member models of how the ice would be removed. In one, the flow is such as to remove all the ice above buoyancy and none below, resulting in the end in an ice shelf that is just barely afloat everywhere. In that extreme, all the ice removed would contribute to sea-level rise. In the other extreme, all the ice is removed; only half then contributes to sea level. In any real case, the situation would be intermediate: some of the ice below sea level would be removed along with that above. Thus the increase in outflow that would be required for a "rapid" rise in sea level (as defined above) becomes a factor of 10–20.

This would be a huge change: glaciers and ice streams that now typically flow at speeds of 0.5–2 $km\ a^{-1}$ would have to accelerate to an average of 10 or 20 $km\ a^{-1}$, substantially faster than any present-day glacier anywhere in the world. An increase of this magnitude, whether internally generated or in response to a climatically produced alteration in the boundary conditions, could come about only from a massive instability. What theoretical or observational evidence is there to suggest the existence of such an instability?

2. THEORETICAL STUDIES

Twenty years ago the concept was developed that a marine ice sheet is inherently unstable, because of a mismatch in ice-mass flux at the junction, known as the grounding line, between the grounded ice (ice resting on a solid bed) and the adjacent floating ice shelves (Weertman, 1974). The mismatch would result in a change in the thickness of the ice at the grounding line that would cause the grounding line either to advance or to retreat and, on a flat bed or one that becomes deeper toward the center of the ice sheet (the case with the WAIS), to continue advancing or retreating either to the edge of the continental shelf (unstable advance) or into the central interior until all the ice was afloat (unstable retreat). Whether this junction, the "grounding line", advances or retreats depends in the theory upon the initial depth of water at the grounding line: when the height of sea level is less than a critical value, as in glacial times, unstable advance results, but a high sea level, as at present, leads to unstable retreat. The WAIS owes its existence, in an extension of that concept, to frictional drag from a combination of grounded "pinning points" in the ice shelves and shear resistance along the sides of their enclosing embayments. That drag creates a "back pressure" from the ice shelves, which restrains the outflow of the grounded inland ice (Thomas and Bentley, 1978; Thomas and others, 1979). If oceanic warming and circulation changes were to thin the ice shelves rapidly, the WAIS would collapse in as little as a century by a catastrophic grounding-line retreat, causing sea level to rise at a mean rate of some 50 $mm\ a^{-1}$.

The idea of marine-ice-sheet instability, however, was based on a simplistic model of a marine ice sheet in which a discontinuity in physics at the grounding line, together with a required continuity in the ice thickness, led to the modeled instability. The reality of the WAIS is that its activity is dominated by fast-flowing, wet-based ice streams whose characteristics blend gradually into those of the ice shelves and whose response times to changes at the grounding line appear to be very rapid (Alley and Whillans, 1991).

Just what the dynamic consequences of the ice streams are for the stability of the WAIS is much in dispute. On the one hand, the inherent ability of ice streams to transport ice rapidly from the interior to the ocean indicates, in the view of some glaciologists, an enhanced capability for a drastically accelerated output flux. A contrary view is that the rapid response time of ice streams removes the flux imbalance at the grounding line that was the basis of the instability model and that the purported grounding-line instability very well may not exist.

Recent work is equivocal. The best model study to date is that by MacAyeal (1992) of the possible behavior of the WAIS over the last million years, because it incorporates ice streams and their slippery beds into the numerical model (although not in an entirely realistic way). That study leads to the conclusion that the WAIS might indeed have disappeared completely at times in the past; the maximum rate of collapse in his model yielded a contribution to sea-level rise about equal to the present-day rate. A particularly important aspect of MacAyeal's model results is that the collapses occur at times irregularly spaced relative to the ice-age cycle, not preferentially during interglacial periods, because of the long time constant of the subglacial system. His modeling yielded three collapses in 10^6 years; if each lasted a few thousand years (e.g. a 6 m rise in sea level at 2.5 $mm\ a^{-1}$) a collapse would have been in progress on the order of 1% of the time. However, when a collapse is not already in progress, as at present, the chance that one will be *initiated* within the next century, say, is about $3 \times 100\ a/10^6\ a$, i.e. only about 0.03%.

MacAyeal's (1992) model also produced iceberg pulses, with fluxes of 1000–3000 $km^3\ a^{-1}$ (3–10 $mm\ a^{-1}$ sea-level rise) lasting a few decades, about ten times during the million-year model run. These too occurred pseudo-randomly, so the chance of being within a century of such a pulse would be about 0.1%.

These quantitative results are, of course, not precise, and should not be taken literally, as some approximations in MacAyeal's model remain crude, particularly those relating to the bed and to horizontal advection, which is not considered, thus precluding thermodynamic feedback with the flow from upstream (MacAyeal, 1992). I cite them only to show that even in a model that produces collapses, collapses are inherently infrequent, are not synchronized with the climate cycle owing to the long response time of the ice sheet, and do not necessarily produce a drastic change in the rate of sea-level rise. But it is likely that these general characteristics of collapses will carry over to other, future models, because of the importance of basal processes, and hence long and probably non-linear response times, to ice-sheet dynamics.

Recent theoretical treatments tend to support the idea of stability rather than instability of a marine ice sheet. In these analyses the ice shelves turn out to be unimportant to the maintenance of the inland ice. One of the reasons for this is the removal from the models of an unnecessary constraint that the ice thickness must be continuous across the grounding line (Hindmarsh, 1993), with the consequence that even total removal of the ice shelves might not result in a large increase in the outflow (personal communication from R. C. A. Hindmarsh, 1997). Furthermore, several studies indicate that the transition zone between the grounded and floating ice does not play an important role; in particular, that it does not act as a source of instability (Van der Veen, 1985; Herterich, 1987; Huybrechts, 1990; Barcillon and MacAyeal, 1993; Hindmarsh, 1993, 1996; Lestringant, 1994a, b; personal communication from P. Huybrechts, 1997). One study indicated that tripling the present-day melt rate beneath the West Antarctic ice shelves would lead to a rise in sea level of only 0.3 m in 500 years (Huybrechts and Oerlemans, 1990).

A recent development that does suggest a dramatic instability is the evidence for sudden, massive outpourings of icebergs from the Laurentide (Canadian) ice sheet during the last ice age ("Heinrich events"; Broecker, 1994). MacAyeal (1993) modeled these events by a thermally activated growth–collapse cycle of ice in the Hudson Bay drainage system; in his recent work he finds a maximum rate of mass flux during a collapse on the order of 3000 $km^3 a^{-1}$ (personal communication from D. R. MacAyeal, 1997). That, coincidentally, is just the amount needed for a "rapid" rise in sea level (by my definition). Furthermore, the Hudson Bay drainage system is comparable in area to the drainage system of the "Ross Embayment" (the portion of the WAIS that discharges into the Ross Ice Shelf); if the Ross Ice Shelf did not exist (MacAyeal still believes that ice shelves are important and essential), the WAIS ice stream would be in exactly the configuration used for the Hudson Strait modeling (personal communication from D. R. MacAyeal, 1997). But MacAyeal's theory depends upon transformation of the bed of a potential ice stream from frozen to melting. This process is not applicable to the West Antarctic ice streams since they are already melting at their beds and consequently should be in the "purge" state, yet nine out of ten exhibit a positive or near-zero mass balance (flux in, by snow accumulation, minus flux out, by ice flow) (Bentley and Giovinetto, 1991; Lucchitta and others, 1995). It is questionable whether a large increase in the speed of ice-stream movement could be induced (Radok and others, 1987). Of course, MacAyeal's (1993) model for the Heinrich events may not be conceptually correct (for example, Hulbe has developed a model of ice shelves, in which debris-rich basal ice is protected by the accretion of saline marine ice, that could yield Heinrich layers without any glacial surges (Hulbe, 1997); if a different mechanism obtained, perhaps it would also apply to the WAIS. Nevertheless, no model of the Heinrich events that would also imply WAIS instability has been put forward to date. The theoretical basis for claims of instability remains weak.

3. FIELD OBSERVATIONS

Thus the modeling results yield no compelling evidence for "rapid" sea-level rise from the WAIS. Is that also the case for the glaciological field evidence? Consider first the drainage system that flows into Pine Island Bay on the Amundsen Sea. This might be a particularly likely site for accelerated flow since there are indications that an ice shelf filling the bay may have disappeared in recent geologic time (Kellogg and Kellogg, 1986), thus reducing the restraint on the inflowing ice streams (Pine Island and Thwaites Glaciers). But measurements indicate a mass balance of this system that is not significantly different from zero (Bentley and Giovinetto, 1991; Lucchitta and others, 1995). Measurements of flow rates on the floating parts of these two ice streams, as measured by satellite-image techniques, do indicate increases over the last decade or two (Ferrigno and others, 1993; Lucchitta and others, 1995), but the reality of these increases is uncertain (personal communication from B. K. Lucchitta, 1997). Furthermore, velocity increases on the Thwaites Glacier tongue, at least, are most likely due to the dramatic shortening of the tongue over recent decades (Ferrigno and others, 1993). So far only one set of velocity measurements has been made on the grounded ice of these glaciers.

Additional evidence on the insensitivity of glacier input flux to ice-shelf back-pressure comes from outside the WAIS. The small Wordie Ice Shelf in the Antarctic Peninsula (Fig. 1) has virtually disappeared over the last decade (Doake and Vaughan, 1991), yet recent measurements reveal no speed-up in the flow rates of the glaciers flowing into it (Vaughan, 1993). Also, a small field experiment on the Ekström Ice Shelf (Fig. 1) conducted in 1993–94 showed that the transition zone between grounded and floating ice is very narrow (its width is only a few times the ice thickness), which suggests that the flow regimes in the two regions are essentially independent of each other (Mayer and Huybrechts, 1994; personal communication from P. Huybrechts, 1997).

In the "Ross Embayment", field evidence (distribution and depths of buried crevasses) reveals that sudden reorganizations of the ice streams have occurred in the last 1000 years. Ice Stream C abruptly stagnated (Retzlaff and Bentley, 1993), one of the boundaries of neighboring Ice Stream B underwent a sudden lateral jump of 10 km or so (Bentley and others, in press), and part of Ice Stream A became quiescent (personal communication from S. Shabtaie, 1997). In addition, parts of the system are grossly out of balance today: Ice Stream B is hyperactive (strongly negative mass balance), Ice Stream C is stagnant (strongly positive mass balance) and Crary Ice Rise (an island of grounded ice in the Ross Ice Shelf near the mouth of Ice Stream B) is growing and changing the regional velocity field (MacAyeal and others, 1987; Bindschadler, 1993).

If the "Ross Embayment" system were unstable, one might expect these major dislocations to have caused some large changes in the outflow of ice into the Ross Ice Shelf. Observations of the Ross Ice Shelf itself can be used to test this possibility for the last 1500 years, because tracers of past flow preserved in the shelf can be compared with the present-day flow of the ice (Bentley and others, 1979; Neal, 1979; Bentley, 1981; Jezek, 1984). Large surges of the inland ice would be recorded as distortions of the flow tracers. Indeed, one striking deformation of the flow tracers has been found (Fig. 2); analysis indicates that perhaps 800 years ago there was a large pulse of ice from the vicinity of Ice Streams A and B, perhaps due to differential variations in ice-stream discharge or perhaps due to the incorporation of a large ice "raft" (Casassa and others, 1991), but it also shows that the flow after that pulse reverted to what it was beforehand. There is no sign of a major change in outflow at the time of

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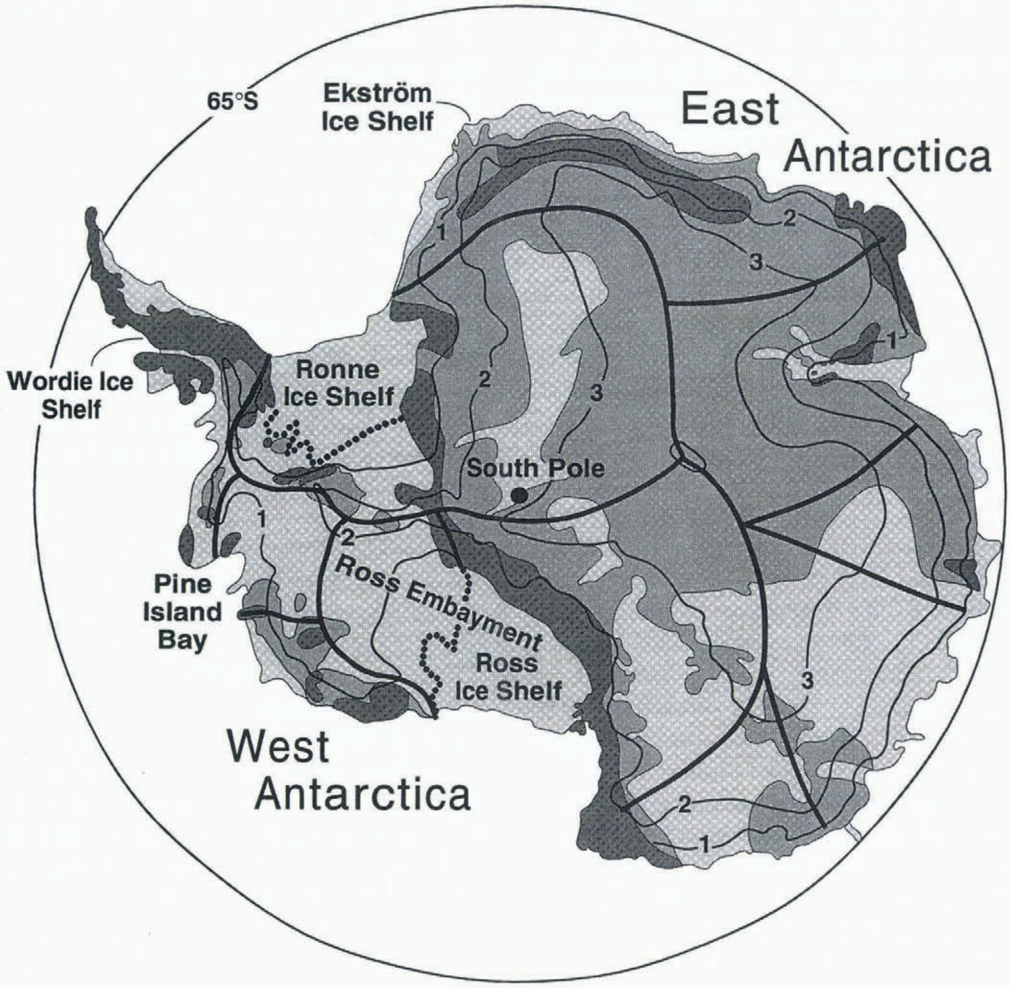

Fig. 1. Map of the inland (grounded) ice sheet of Antarctica, showing surface elevations (black contour lines; heights in km), mountainous regions (dark gray) and sections of the ice sheet where the bed is above (medium gray) and below (light gray) sea level. The heavy black lines divide the principal drainage systems. The grounding lines of the Ross and Filchner–Ronne Ice Shelves are designated by the black dotted lines.

the reorganizations of Ice Streams B and C, about a century and a half ago.

Taken as a whole, the WAIS "Ross Embayment" system is nearly in mass balance (Bentley and Giovinetto, 1991). Furthermore, the proportion of ice flowing into the Ross Ice Shelf from East and West Antarctica, respectively, has remained approximately constant over the full 1500 years. This is shown by the concordance between flowlines and flow tracers all the way across the grid eastern part of the ice shelf, where the flow is from East Antarctica (Fig. 3). This concordance implies that the total outflow in the "Ross Embayment" has remained relatively unchanged despite the large internal perturbations, since a large change in that outflow at some time within the last 1500 years would have caused a corresponding distortion in the flowlines from East Antarctica, the total outflow from which presumably has been fairly steady over time. Nearly constant total flow from the WAIS at times of large internal disturbances points to a stable, not an unstable, system.

Glaciological studies of several types have all indicated that there has been no drastic change over the last 30 000 years in the height or flow of the ice sheet at Byrd Station, which lies in the West Antarctic interior within the "Ross Embayment" (Whillans, 1976, 1983; Raynaud and Whillans, 1982). Field measurements on the surface indicate that the ice there and elsewhere in the interior "Ross Embayment" is now thinning slowly (by a few to about 10 cm a^{-1}), perhaps partly in response to climatic warming about 10 000 years ago at the end of the last ice age (Whillans, 1983; Hamilton and Whillans, 1997). White and Steig (1997) interpret diverging trends in oxygen isotope ratios in ice-core records from Byrd Station and Taylor Dome (in the Transantarctic Mountains near McMurdo Sound) as indicating a drop in surface elevation at Byrd Station of about 400 m over the last 6000 years ($\approx$7 cm a^{-1}). This concept is in accord with glacial geologic studies by G. H. Denton and his group, mostly in the region around McMurdo Sound, which indicate that the grounding line in the "Ross Embayment" retreated slowly to its present position over the last 7000 years or so (Hall and Denton, 1996).

Interestingly, the first results from radar altimetry using the European remote-sensing satellites ERS-1 and ERS-2 suggest that the ice surface in central West Antarctica has been slowly rising (at a few cm a^{-1}) over the mid-1990s (Wingham and others, 1997). Elsewhere in West Antarctica north of 81.5° S (the limit of coverage of the ERS satellites) the surface height has not changed observably, i.e. by more than a few cm a^{-1}. There is no suggestion in the radar altimetry of a large imbalance of either sign anywhere in this region, which includes the drainage basins of the Ronne Ice Shelf and Thwaites and Pine Island Glaciers.

Study of the third major drainage from the WAIS, into the Ronne Ice Shelf, also suggests that there is no gross discordance between the present velocity vectors and flow tra-

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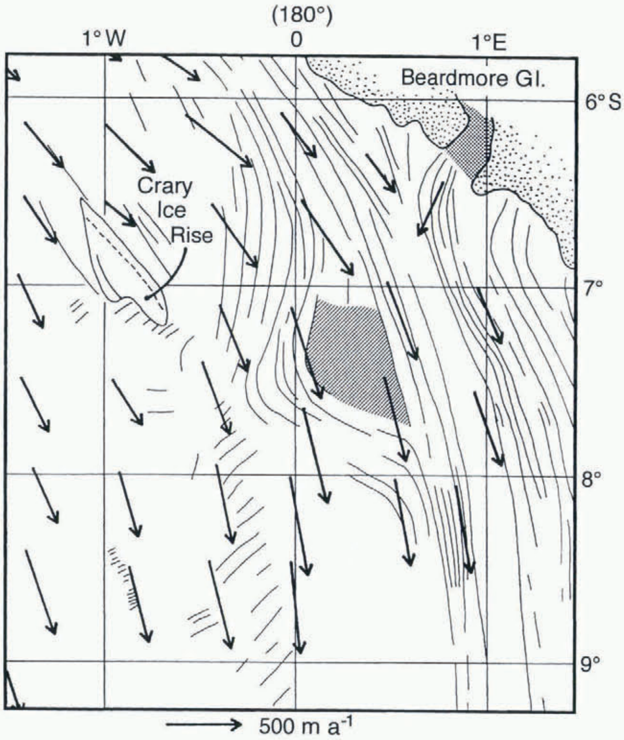

Fig. 2. Sketch map of features identified on advanced very high-resolution radiometer imagery in the central Ross Ice Shelf (the grid coordinates are the same as in Figure 3). The hatched area bounded by curvilinear flow stripes is interpreted to be caused either by an ice raft or by a large differential variation in the outflow of Ice Streams A and B some 800 years ago. From Casassa and others (1991).

cers in the ice shelf, although the evidence is limited (personal communication from C. S. M. Doake, 1997).

4. THE FUTURE

In the light of the evidence for recent stability, it is difficult to see how climate warming (whether anthropogenic or natural) could trigger a collapse of the WAIS in the next century or two. Ice sheets take thousands of years to respond to changes in surface temperature, because it takes that long for the temperature changes to penetrate close to the bed, and only there could increasing temperatures affect the flow rates (Whillans, 1977). Oceanic warming could cause thinning of the ice shelves, but recent global-circulation-model studies have suggested that oceanic warming in the far Southern Ocean from, say, an enhanced greenhouse effect would be delayed by centuries compared to the rest of the world, because of the large-scale sinking of surface waters around Antarctica (Manabe and others, 1991). Furthermore, for reasons already cited, it is doubtful that ice-shelf thinning would have any drastic effect on the inland ice.

The only climatic change that is likely to have an immediate effect on the Antarctic ice sheet is the increase in precipitation that probably will accompany warmer air temperatures. Increased precipitation will increase the mass input onto the ice sheet without causing any balancing increase in outflow for centuries. In the short term, the ice sheet probably will grow slowly (relative to its current state of mass balance) (Fortuin and Oerlemans, 1992).

There remains the possibility that the WAIS will shrink rapidly in the next century or two, owing to its own natural variability. Based on the studies by MacAyeal cited above, and on the more general idea of an unsynchronized collapse occurring about once every glacial cycle, I estimate the chance of that to be on the order of one in a thousand. Obviously, this is not a number to be taken literally; nevertheless, I believe it puts the threat of rapid sea-level rise from a WAIS collapse in a realistic perspective.

Bindschadler (1997) argues that neither climate change nor the response of an ice sheet thereto is truly random; the problem is that models of ice-sheet dynamics are still woefully inadequate. That is true, but it does not provide any help in estimating the likelihood of collapse. My point (Bentley, 1997) is that a major catastrophe would have to befall the WAIS to cause a "rapid" rise in sea level and that there is no theoretical or observational reason to suspect that such a catastrophe is imminent, if, indeed, one can occur at all. I use a pseudo-random model based on the work of MacAyeal (1992) to obtain a rough estimate of the probability of a collapse event, because there is nothing better to use; improvements in the physics of the ice-dynamic models are, a priori, just as likely to yield a lesser likelihood of collapse as a greater one. Bindschadler (1997) further points to major changes in the WAIS that have occurred in the past, including the last 11 000 years, as part of the worldwide retreat from the Late Glacial Maximum. But the evidence he himself cites indicates that a 10–20 m contribution to sea level was spread out over most of that time, so that the corresponding mean rate of sea-level rise was only 2 mm a^{-1}, even in that major event. That hardly points to a much larger rate of collapse in the near future.

Finally, it is perhaps worth noting that (other things being equal) the more rapid and abrupt, and therefore shorter-lasting, a hypothetical rise in sea level (supposed to occur at some time in a glacial cycle) is taken to be, the less likely it is to be initiated within a particular short period of time, such as the next century.

5. CONCLUSIONS

In the last thousand years, the total outflow in the "Ross Embayment" has remained relatively unchanged despite large internal perturbations. That is the mark of a stable, not an unstable, system.

There is no evidence to suggest, or theoretical reason to suppose, that other drainage systems within the WAIS behave in a fundamentally different way.

Consequently, the likelihood of a "rapid" rise in sea level in the next two centuries as a result of anthropogenically caused climate change acting on the West Antarctic ice sheet is vanishingly small. The likelihood of a naturally caused "rapid" rise is on the order of one in a thousand.

These conclusions are weakened only slightly if "rapid" is redefined as twice rather than five times the present rate, because even to produce that lesser flux the WAIS would have to accelerate its outflow by a factor of four or five, which would still require strongly unstable behavior.

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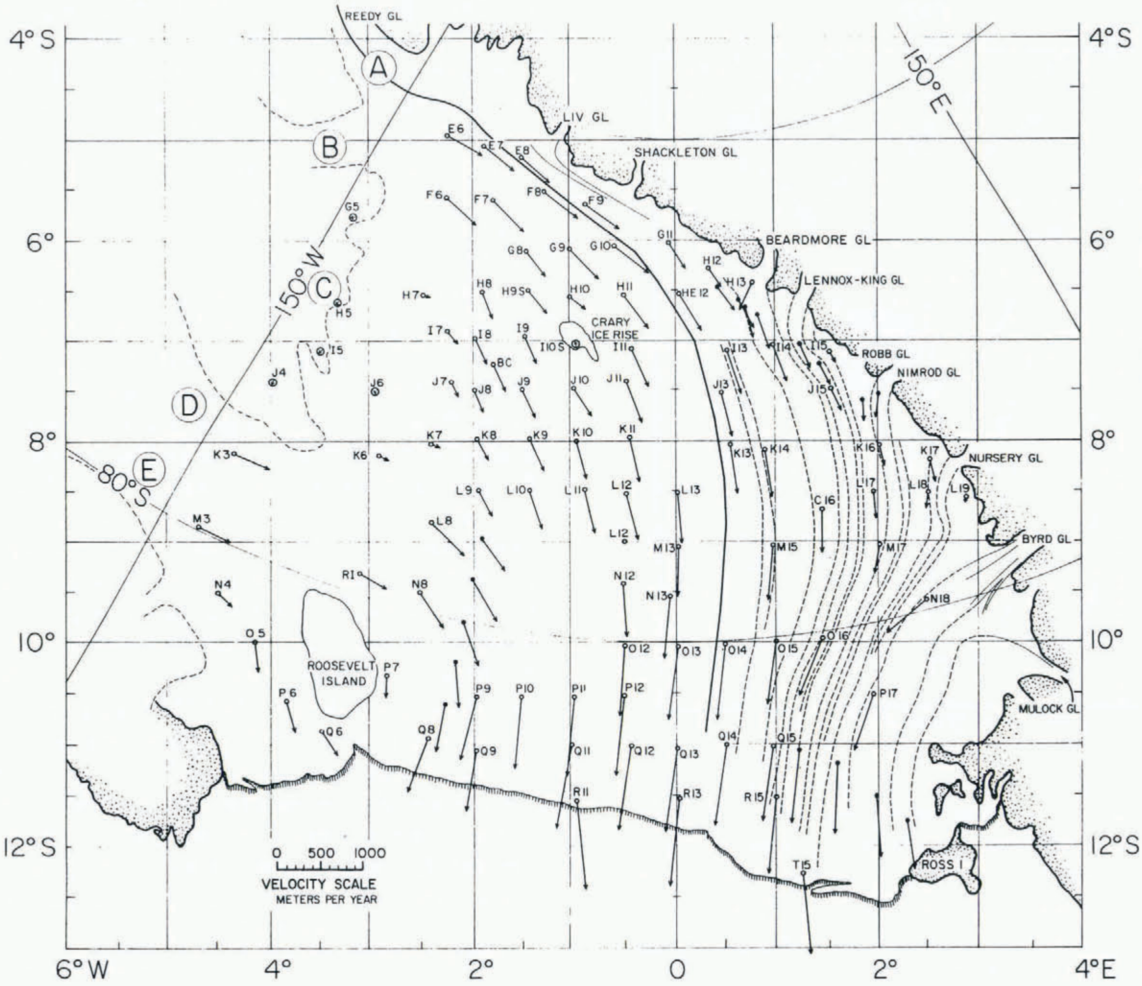

Fig. 3. Velocity vectors on the Ross Ice Shelf, determined from Doppler satellite tracking data (arrows; from Thomas, and others, 1984), and flowlines based on variations in radar-echo strength (dashed lines). The heavy line in the central part of the map represents the boundary between East and West Antarctic ice. The grid coordinate system has its origin at the South Pole, with north toward Greenwich. From Bentley and Jezek (1981).

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