PERSPECTIVES: GEOSCIENCE

Future of the West Antarctic Ice Sheet

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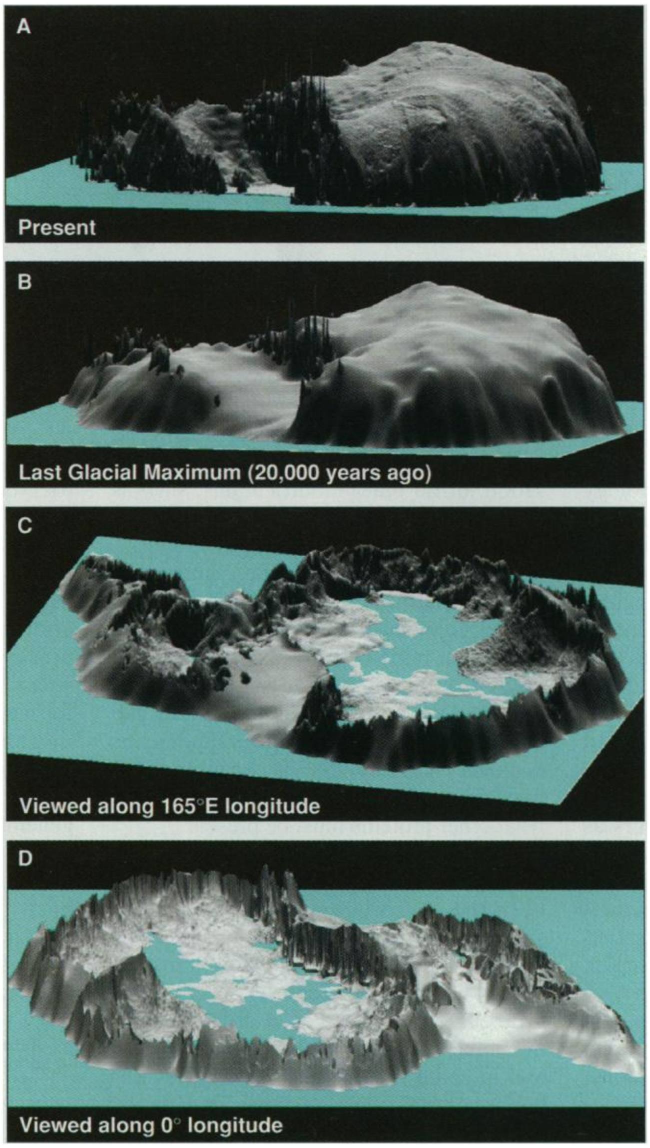
There has been much debate over what would happen if the West Antarctic Ice Sheet were to collapse into the ocean. The economic and ecological impacts of the resulting 5-m increase in global sea level would depend greatly on the rate at which this change might take place. Most attempts to quantify the probability of a collapse have been limited to assumptions of "quasi-randomness" of these events and the results of Monte Carlo simulations (*1*). But recent information on past ice-sheet extent and current behavior are providing another view of its future lifetime and its potential contribution to sea level.

Concern over the West Antarctic Ice Sheet is based on the past episodes of rapid sea-level rise and their correlation with rapid discharge of grounded ice within basins of former ice sheets occupying marine basins. West Antarctica is the most prominent remaining ice-filled marine basin on Earth. It is drained by fast-moving ice streams that extend far into the ice-sheet interior. Theoretical analysis of such "marine-based" ice sheets suggests that they are unstable (*2*). A model incorporating interaction between the ice, subglacial water, and till also exhibited periodic collapses of the ice sheet (*3*).

The Antarctic Ice Sheet was much expanded during the Last Glacial Maximum, 20,000 years ago. Models of individual flow lines within the ice sheet have been revised to estimate the former shape of the ice sheet (see figure, panel B) (*4*). In West Antarctica, the ice sheet has lost two-thirds of its mass since the Last Glacial Maximum, a volume of ice sufficient to raise sea level 11 m (*4*). The largest losses have been where the former grounded ice sheet retreated, forming the present-day Ross and Ronne/Filchner Ice Shelves (see figure, panels C and D). Deeper in the interior, the ice thickness has not changed much (*5*). Changes are also slight in East Antarctica. Around the perimeter, the most seaward ice has been lost because of rising sea level. The only other major loss of East Antarctic ice is in the Lambert Glacier region, where similar ungrounding formed the Amery Ice Shelf.



Ice sculpting. Three-dimensional perspectives of Antarctica at present (**A**) and at the Last Glacial Maximum (**B**). Vertical scale is exaggerated by a factor of about 500. View southward along the Transantarctic Mountains shows the considerable retreat of the West Antarctic Ice Sheet (left) compared with the East Antarctic Ice Sheet (right). Source data for the Last Glacial Maximum are from Hughes (*4*) and for the present shape are from Bamber (*21*). Difference between present and Last Glacial Maximum elevation of Antarctic Ice Sheet viewed along 165° longitude (**C**) and 0° longitude (**D**).

New research provides "way points" in the retreat history of the West Antarctic Ice Sheet (see graph). Most of the data come from analyses of sediment cores from the western Ross Sea. Radiocarbon dating of the ice-front retreat chronology is most reliable, owing to the increase in biogenic material deposited on the sea floor when ice retreat results in open marine conditions (*6*). A multivariate approach was used to date ungrounding 11,700 years ago near Drygalski Ice Tongue (*7*). Some controversy on the fullest extent of the grounded ice sheet still exists, but the range of disagreement does not affect my interpretation of the data. Finally, terrestrial surface exposure dates in the McMurdo Sound area have been used to determine that grounded ice left that area 7000 years ago (*8*).

These way points are combined by projecting them onto a flow line following ice stream B and its corresponding trough in the Ross Sea (*9*). Some cores (KC37, KC31, PC26, PC29, and Df80-117) lie westward of this flow line, in ice that may have originated in East Antarctica; however, large embayments are absent in the present-day ice front, and retreat was probably roughly uniform across the ice front. Along this flow line, the present termination of grounded ice is 700 km downstream of the ice divide, and the continental shelf lies 2100 km from the divide.

The retreat rate of the ice front has diminished over time. The slower ice-front retreat, relative to retreat of the grounding line (the junction between grounded ice and floating ice shelf), results in an expanding Ross Ice Shelf. The ice front now appears to be nearly stable, possibly a result of the mechanical support afforded by Ross Island and Roosevelt Island at either end of the ice front. The rapid retreat between core locations KC39 and KC37 might be real but could also be related to the fact that each is located in

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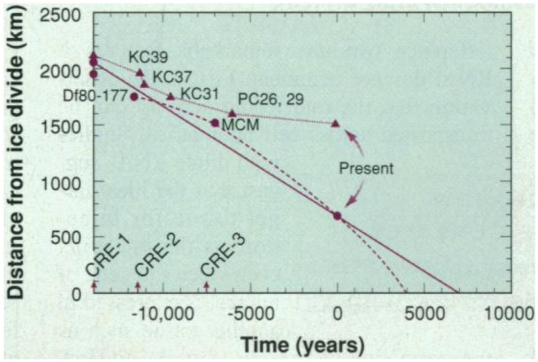
separate sea-bed troughs. Short-lived asynchronous retreat along these troughs cannot be ruled out.

A linear fit to the grounding-line retreat data implies an average rate of retreat of 100 m/year. At this rate, the grounding line would reach the ice divide in another 7000 years, supplying a sustained contribution of 0.8 mm/year to rising sea level. This amount would reconcile the disagreement noted by Meier (*10*) between the sum of present estimates of sea-level contributions and observed rates if the Antarctic Ice Sheet mass balance is replaced by this West Antarctic value and if the Greenland Ice Sheet mass balance is reduced to zero, according to recent re-analysis of satellite altimetry (*11*).

A second-order fit to the grounding-line retreat data results in an accelerating retreat model. In this case, the initial grounding-line position is ignored because both the date and position are uncertain. This model, however, predicts a 4000-year lifetime for the ice sheet, a current retreat rate of 150 m/year, and a current sea-level contribution of 1.3 mm/year. Support for these higher rates of retreat can be found from direct measurements at the head of ice stream B. There, rates of upstream migration have been inferred from progressive crevasse formation (*12*) and from local mass imbalance (*13*). Ice-stream heads are almost certainly out of equilibrium because lateral and vertical convergence of flow (each roughly a factor of 2) into an ice stream is overcompensated by the increase in velocity (typically an order of magnitude). Mass continuity of ice dictates that the uncompensated acceleration must result in thinning at the ice-stream head, which will drive the head farther inland (*14*). Given that lengths of West Antarctic ice streams fall in a narrow range, I suggest that ice-stream grounding lines should retreat in step with inland migration of their heads.

Although these data seem to present a consistent picture for a portion of West Antarctica, they must be examined for their overall representativeness of West Antarctica where recent reports indicate that other ice streams may be more stable. One method to examine this question is to consider the ice-sheet mass balance required for a net contribution of 0.8 mm/year to sea level from all of West Antarctica (the above linear model). The total amount of water required from the ocean for 1 year's snowfall in West Antarctica lowers sea level roughly 1.5 mm/year (*15*). To have a net positive contribution of 0.8 mm/year to sea level, West Antarctic discharge into its ice shelves and the ocean must equal 2.3 mm/year of sea-level equivalent. This means the overall mass balance of the West Antarctic Ice Sheet must be –53%. Ice stream B's mass balance is –50% (*16*), but other ice streams have lower mass imbalances (although most are negative). Ice streams feeding the Ronne Ice Shelf appear more stable than those feeding the Ross Ice Shelf, whereas Pine Island Glacier, a major West Antarctic outlet flowing northward into the Amundsen Sea was recently identified as experiencing grounding-line retreat of 1200 m/year (*17*). The evidence for a large negative mass balance for all of West Antarctica is inconclusive [see page 456 (*18*)].



A hasty retreat? Positions of grounding line (circles) and ice front (triangles) in the western Ross Sea versus time from present. Positions are projected onto a flow line following ice stream B, West Antarctica. Labels of ice-front positions denote cores collected in western Ross Sea (*7*). Former grounding-line positions are from core Df80-177 near Drygalski Ice Tongue (*8*) and in the vicinity of McMurdo Sound (*9*). Positions at –14,000 years are estimates of positions during the Last Glacial Maximum. Lines represent possible retreat behavior discussed in text.

If the slope of the linear grounding-line retreat model is too high, more variable retreat must have occurred. In particular, the retreat history between McMurdo Sound and the present position must have included a period during which retreat was more rapid than the linear model. From geologic evidence on Ross Island (in McMurdo Sound), Hall and Denton (*8*) have argued for a period of rapid retreat 7000 years ago.

Although the temporal resolution of the data used here is sparse, there are suggestive coincidences with episodes of sudden increases in sea level. The graph includes the dates of three catastrophic rises (CRE-1, -2, and -3) when sea level rose at rates as high as 60 mm/year (*19*). CRE-1 may coincide with the initiation of retreat (although the initial retreat date is uncertain), CRE-2 matches the apparent sudden ice-front retreat from KC39 to KC37 (*20*), and CRE-3 is close to the sudden retreat in McMurdo Sound argued by Hall and Denton (*8*).

Consideration of past data near the ice stream B flow line thus seems to provide bounds on the future lifetime of the West Antarctic Ice Sheet of between 4000 and 7000 years. These bounds are qualified by the ability of ice stream B to represent the entire West Antarctic Ice Sheet; however, the length of this flow line and the large amount of sea-floor sediment analysis in the western Ross Sea make it the best candidate for this examination. The West Antarctic Ice Sheet has undergone much larger changes than the adjacent East Antarctic Ice Sheet and has raised sea level 11 m over more than the past 14,000 years at an average rate of 0.8 mm/year. Grounding-line positions support a model of accelerating retreat, but the required overall mass balance in West Antarctica would need to be considerably more negative than can be confirmed from current data. Thus, a more erratic history is still possible with a variable retreat rate and a shorter lifetime. Intervals of most dramatic change appear to coincide with episodes of rapid sea-level rise, but the cause-and-effect relation remains unclear. More accurate prediction of the future of the West Antarctic Ice Sheet requires an understanding of the dynamics responsible for its behavior and more data on its history.

References and Notes

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