CLIMATE CHANGE

Greening the Antarctic

The ecological consequences of climate change in the polar regions are becoming increasingly evident. A study in the Antarctic now shows how terrestrial vegetation may be responding to rising temperatures. Amesbury *et al.* analyzed peat cores spanning the past 150 years from moss banks in the western Antarctic Peninsula. Multiple proxies in the cores—including carbon isotope discrimination, populations of testate amoebae, and the balance of moss growth and decomposition—are indicative of an increase in biological activity over the past 50 years, coinciding with the increasing rate of temperature rise. This activity is likely to lead to further greening in the Antarctic, as is already evident in Arctic landscapes. —AMS

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Antarctic moss banks show increased biological activity consistent with the effects of warming temperatures.

CLIMATE

Is ice sheet collapse in West Antarctica unstoppable?

Most climate scenarios paint a bleak future for the West Antarctic Ice Sheet

By **Christina Hulbe**

Forty years ago, Mercer raised an alarm by connecting climate warming with collapse of the West Antarctic Ice Sheet (WAIS) and substantial sea level rise in both the past and future (*1*). Since then, observations have proliferated, yielding improved understanding of ice sheet processes and making clear that the WAIS is highly vulnerable to future climate change (*2*). Yet, despite this progress, projections of the future rate of change can vary by a factor of 10 for the same climate warming scenario, producing different time scales for collapse; whether the model ice sheets collapse depends on the level of warming (*3*, *4*). Better understanding of the different model outcomes can help to inform how we set greenhouse gas emissions goals and plan for future sea level rise.

The fundamental challenges to WAIS stability arise from the fact that its base rests mainly on the seafloor. Ice that accumulates in the Antarctic interior flows toward the coast, speeding up and thinning in the process. Because the bed lies below sea level, thinning eventually leads the ice to float on the ocean surface, forming an ice shelf. Ice shelves connect the WAIS with the ocean and with relatively warm parts of the atmosphere, presenting a pathway for climate warming to drive rapid change in the grounded ice (*1*).

If we were to take only one measure of WAIS well-being, it would probably be the position of the grounding line, the line of transition from the grounded to floating parts of the system. Because it is floating, the ice shelf has already made its contribution to sea level, but the geometry and flow of the shelf affect the position of the grounding line. This raises the possibility that change in the ice shelf can drive change at the grounding line, which can in turn drive change in the ice sheet.

Flux through the grounding line is the product of the depth-average ice speed and the thickness at that boundary. The speed itself depends on the ice thickness, making flux at the grounding line a strong function of ice thickness there. Because the seafloor grows deeper and ice thickness increases toward the interior of the WAIS, a perturbation that causes the grounding line to retreat also tends to increase the flux. Once initiated, retreat always proceeds into thicker ice and may thus be unstoppable (*5*).

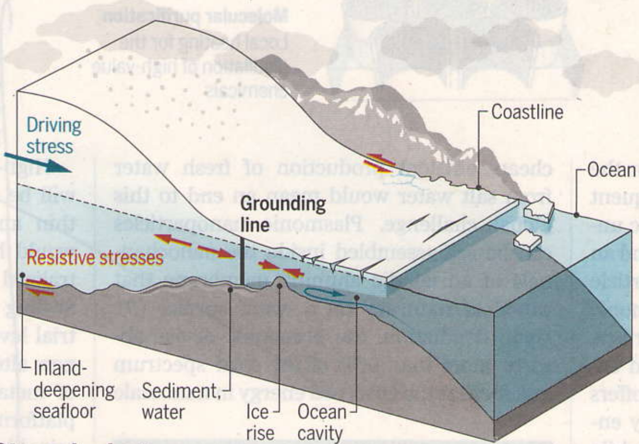
Speed at the grounding line also depends on the stress gradient across the transition. The budget between driving stresses due to gravity and resistive stresses arising from contacts with materials at the boundaries of the ice determine the gradient. In many parts of the ice sheet, particularly its marine sectors, materials at the boundaries are weak, and the stress balance is nonlocal. Traction under fast-flowing parts of the grounded ice sheet, traction along irregularly shaped coastal margins, and compression where the seafloor shoals and the floating ice runs aground to form ice rises and ice rumples all modify flow across the grounding line and therefore mediate grounding line position (*6*–*9*).

Whether or not a climate forcing that causes an initial retreat of the grounding line yields self-sustained retreat depends on both the inland-deepening bed and a positive feedback in the stress budget that continually overcomes the flow-limiting effects described above. Additional processes—such as isostatic rebound, subglacial sediment transport and deposition, ocean circulation in the cavity under the ice shelf, crevasse propagation, and meltwater on the ice shelf surface—also change conditions at the boundaries of the floating ice and at the grounding line (*2*). These processes may either suppress or enhance grounding line retreat and must all be taken into account when we speculate about the future or interpret current observations.

Remote-sensing data show that changes in the thickness and flow of WAIS ice shelves vary in space and time (*10*). Along the Amundsen Sea coast, floating ice is thinning, grounding lines are retreating, and the grounded ice upstream of these boundaries is speeding up. On the Ross and Ronne-Filchner ice shelves, both thickening and thinning are observed, and the

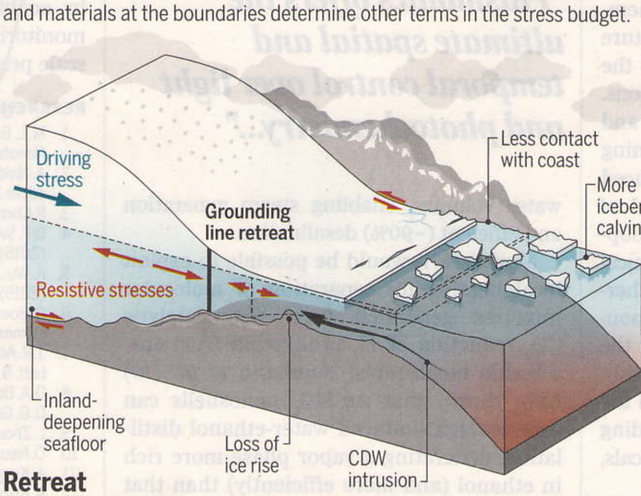
Precarious position

WAIS grounding lines are vulnerable because of the inland-deepening bed and connection to the ocean.



Stress budget

Ice flows in the direction of its surface slope due to gravity. Properties of the ice and materials at the boundaries determine other terms in the stress budget.



Retreat

An external forcing can cause runaway grounding line retreat if the perturbation to the stress budget is self-sustaining.

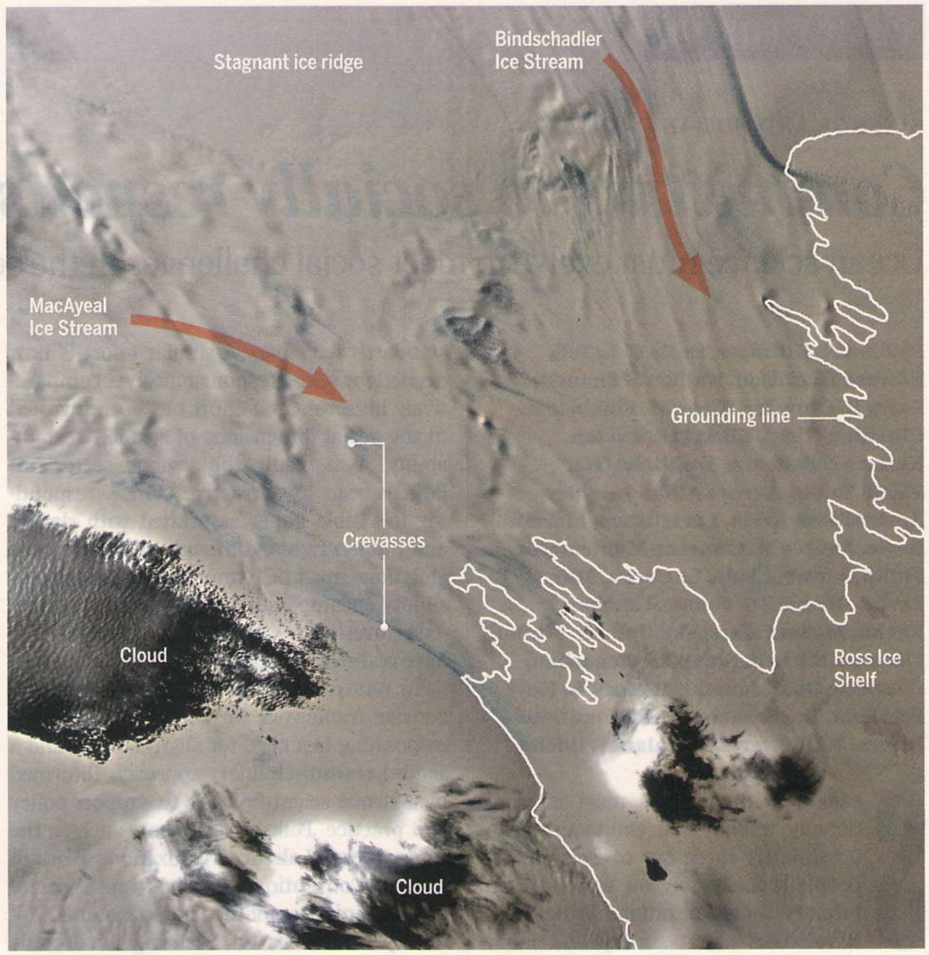
GRAPHIC: A. KITTERMAN/*SCIENCE*

sign of the change can switch on multiyear time scales.

Consistent with the theoretical expectation that external environmental forcing can destabilize WAIS grounding lines, the observed retreat and speedup along the Amundsen Sea coast is associated with relatively warm Circumpolar Deep Water (CDW) intruding on the continental shelf (*2*). As long as warm water remains in contact with the ice, retreat is expected to continue. Self-sustained retreat, which would persist even without the marine forcing, requires grounding line stress budgets in which the forces that limit retreat are overcome. That threshold may have already been crossed in the Amundsen Sea, but nothing similar appears to be under way elsewhere in the WAIS. Computational models must be used to determine the circumstances under which other sectors would also start to retreat and cross that threshold.

Ice sheet models driven by the same future-warming scenario yield different rates of change, depending on how boundary processes are parameterized. Yet, the models agree on one thing: When driven with environmental variables from mid-range and high-end global warming scenarios, all predict collapse of the WAIS. At the higher end, marine ice sectors of the East Antarctic Ice Sheet also retreat. However, when the climate forcing follows a lower-end scenario (*11*), retreat is limited (*3*, *4*). In this case, once the melting stops, the rate of retreat declines and grounding lines stabilize. The implication is that large committed retreats, which continue long after the peak in greenhouse gas emissions, may not be inevitable.

Is a future without widespread change in West Antarctica possible? To answer this question, we need to know more about why runaway retreat does not happen in the lower-end model scenarios. Models of Earth system processes are inevitably incomplete, and ice sheet models are no exception. If there is something the models miss entirely, it probably lies in a part of the system that is one of the hardest to observe: the ocean cavity under the floating ice. Progress therefore requires new observational studies of ocean circulation and melt/freeze processes under the ice shelves; more, and more detailed observational and modeling studies of the pathways by which relatively warm water can access the grounding line; and better geologic records of past ocean cavity conditions and grounding line response. Projects such as the growing U.K./U.S. collaboration to study Thwaites Glacier on the Amundsen Sea coast (*12*) and New Zealand–led efforts to monitor ocean circulation and recover sediments under the Ross Ice Shelf are essential to this purpose.



The grounding line of the Ross Ice Shelf at the confluence of MacAyeal and Bindschadler ice streams. The smooth, low slope surface of the ice shelf indicates that the ice is floating. The undulating surface of the ice streams shows that the ice is grounded.

GRAPHIC: ADPATED BY C. SMITH/*SCIENCE* FROM LANDSAT

If the low-end ice sheet scenarios are incorrect or if the required greenhouse gas emissions goals are not achievable, we need to know more about the processes and feedbacks that set the pace of WAIS retreat. This demands not only better knowledge of the processes identified above, but also a better understanding of the vast parameter space in which the models used to project the future operate. Rather than relying on intuition about which processes are the most important and on computation-intensive forward searches of these spaces, we should also use statistical inference to identify model biases and attribute uncertainty in their projections to specific processes (*13*). Without these diverse approaches, we may never correctly understand the implications of different emissions scenarios or whether in addition to centuries of committed ice sheet change, we should start planning for a sea level contribution that reaches 20 cm per decade by the year 2100 (*3*) or rates one-tenth of that amount (*4*). ■

National School of Surveying, University of Otago, Dunedin, New Zealand. Email: christina.hulbe@otago.ac.nz

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