CLIMATE CHANGE

Why Is It Hard to Predict the Future of Ice Sheets?

David G. Vaughan and Robert Arthern

Ice sheet behavior is strongly influenced by processes at its margin and base. Observations of rapid changes at these boundaries are helping modelers to improve predictions of future changes.

The recent report from the Intergovernmental Panel on Climate Change (IPCC) (*1*) highlights the improved accuracy of measurements of current sea-level rise, as well as greater certainty in the projected impacts of global warming on nonpolar glaciers and thermal expansion of the oceans. These advances heighten confidence in projections of the most predictable components of sea-level rise, but the IPCC's projections specifically exclude the contribution that could arise from rapidly changing flow in ice sheets, especially in Greenland and West Antarctica. Why does so much uncertainty surround the future of ice sheets and their impact on sea-level rise?

Compared with the coupled ocean-atmosphere climate system, an ice sheet might seem a rather simple system to model numerically. Ice sheets are composed of a single, largely homogeneous material. Their viscous flow is governed by the Navier-Stokes equation formulated in the mid-19th century. They move so slowly that turbulence, Coriolis, and other inertial effects can be ignored. Stresses within the ice are handled well in the latest generation of ice sheet models (*2*). It is in specifying the stress boundary conditions on two of the ice sheet interfaces—its base and its seaward margin—that the difficulty arises.

At the base of the ice sheet, the stress resisting ice flow can vary by orders of magnitude, depending on the pressure of subglacial meltwater and the slipperiness of sediments. The transience and complexity of water flow beneath ice streams is only now becoming apparent (*3*). At the basal boundary, interactions among water flow, friction, sediment deformation, and heat flow become so intertwined that calculating the resistive stress from first principles tests the ingenuity of glaciologists. Nor is it certain that the basal boundary condition will remain constant on the decadal to centennial time scales that are of interest to the IPCC, especially in Greenland, where meltwater can flood through crevasses to lubricate the base of the ice sheet (*4*).

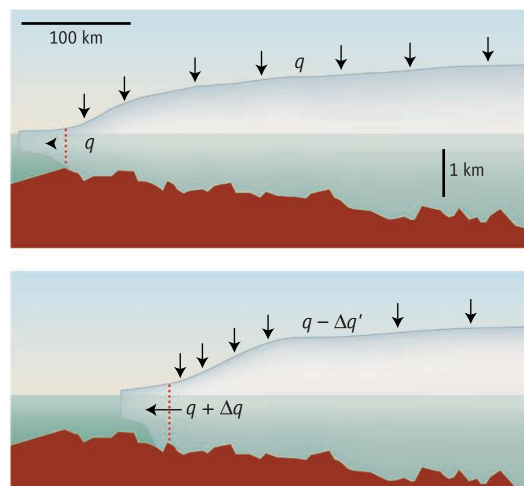
The authors are with the British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge CB3 0ET, UK. E-mail: dgv@bas.ac.uk

At the margin of the ice sheet, the ice begins to float, interacts with the ocean, and eventually calves into icebergs. This boundary controls whether the ice sheet is stable to perturbations, induced perhaps by warmer oceans or atmosphere. Early theories suggested that the location of the margin might be unstable enough that a small perturbation could trigger runaway retreat inland (see the figure) (*5*). Since then, glaciologists have debated whether such extreme behavior could really occur. A new boundary-layer theory for coastal ice shows the way forward (*6*). This theory still needs to be incorporated into large-scale ice sheet models, but early indications are that the instability highlighted by earlier theories should be taken seriously.

Recent observations of widespread acceleration of glaciers draining the Greenland Ice Sheet have brought our uncertainty in specifying these boundary conditions to prominence. Greenland appears capable of responding to changing atmospheric and ocean conditions around its margins much faster than expected (*7*–*9*). The immediate challenge for modelers is to improve the description of the basal and terminal processes such that these changes can be reproduced in model simulations. This is a substantial task, but it is made more feasible by the observations of change that reveal the time scales of response [see also the accompanying Perspective by Truffer and Fahnestock (*10*)], and it provides a superb opportunity to test whether the processes we expect to be important are correctly represented in the models.

In recent years, many changes have also been observed in West Antarctica: thinning and loss of buttressing ice shelves, accelerating glacier flow, thinning of the seaward portion of many glaciers in the region, and inland retreat of the point at which the ice begins to float. The latest theoretical advances have done nothing to allay fears concerning the potential instability of marine ice sheets (*6*) (see the figure). Determining whether small changes could really trigger substantial deglaciation is complicated enough. To compound this, there are no clear-cut records of marine ice sheet deglaciation for comparison, either on Earth today or in the geological record.

There have probably been many marine ice sheet deglaciations during the glacial cycles of the past 2 million years, but the geological record was bulldozed away as the ice sheets subsequently readvanced. Only the record of the last deglaciation, since about 18,000 years ago, remains intact. This deglaciation caused two periods of global sea-level rise at rates far higher than those projected by the IPCC (*2*). However, most of that rise resulted from nonmarine ice sheets, and the sea-level curve on its own does not tell us to what extent marine ice sheets are unstable. Indeed, there is still major uncertainty as to how much of the West Antarctic Ice Sheet survived in recent interglacial periods that were globally warmer than today and that are the best analog for future greenhouse warming. In the absence of a sufficiently well-documented example of marine ice sheet retreat, hypotheses of instability could be missing important processes that limit the rate or extent of retreat, or conversely,



Concerns about stability. The ice sheet covering West Antarctica is the last great marine ice sheet. Its bed lies below sea level and slopes down inland from the coast. The profile shown is based on Thwaites Glacier, West Antarctica (*11*). In the top panel, the ice sheet is in equilibrium; influx from snowfall (q) is balanced by outflow. A small retreat (lower panel) will provoke changes in both the influx and the outflow. If these changes act to promote further retreat, the ice margin is unstable.

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Published by AAAS

promote sudden episodes of retreat.

The accuracy (or "skill") that can be achieved by predictive models rests as much on the quality of data available for testing as it does on the insightful representation of the physical processes. Weather prediction models exhibit a good deal of skill, not because the atmosphere is simpler or better understood than ice flow, but because those models are run and tested with different starting conditions every day and are modified when proved inadequate. Ice sheet models cannot rely so heavily on this cycle of model validation and improvement because of fewer data and much longer time scales.

The uncertainty over the future of the world's ice sheets may persist as the major uncertainty in projections of sea-level rise, perhaps even into the next round of IPCC assessment. Nonetheless, important advances are being made. Ongoing changes in the West Antarctic Ice Sheet and in Greenland are being observed in great detail from satellites (*3*, *9*, *11*); field work is beginning to be directed toward the key areas of the West Antarctic Ice Sheet (*12*); and the history of West Antarctic deglaciation is being constrained on the basis of marine sediment records and dating of rock exposures (*13*). New theories of ice flow appropriate to the coastal boundary are available (*6*). New tools for combining data and models to predict ice flow are also being developed (*14*). New data are coming in and new models are there to be tested—perhaps this is not so different from weather forecasting after all.

The IPCC report has appropriately highlighted the urgent need to reduce uncertainty over the future of ice sheets in Greenland and Antarctica. Accurately predicting how stresses will evolve at the base and the margin has become the priority for ice sheet modelers. Observations are vital for testing these predictions. Recent observations of changes in Greenland and West Antarctica provide the best opportunity for ice sheet modelers to make progress, because they are key to what will happen in the future.

References and Notes

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10.1126/science.1141111

PHYSICS

Critical Insights

Ehud Altman

Ultracold atomic gases provide a new experimental tool that promises to advance our understanding of both classical and quantum phase transitions.

Phase transitions, which mark the appearance of a new ordered state, display some of the most fascinating phenomena in nature. Some of these transitions are discontinuous, that is, there is an abrupt change as a parameter such as temperature is varied. An example is the freezing of water into ice. In this case the properties of water are unaffected by the coming change. Continuous transitions, such as formation of magnetic order in a ferromagnet, are markedly different. As the material approaches the critical point, fluctuations of the new order grow in size and eventually govern the macroscopic properties of the system, making them universal.

On page 1556 of this issue, Donner *et al.* report an experiment with ultracold atomic gases in which they observe these fluctuations directly (*1*), watching how they grow from microscopic to macroscopic dimensions as the transition to a Bose-Einstein condensate is approached. What is even more exciting, the fluctuations are monitored as they evolve in time, potentially offering a glimpse at the dynamics of phase transitions. Such experiments could also be applied to systems of ultracold atoms undergoing quantum phase transitions at zero temperature, promising to advance our rather rudimentary understanding of the dynamics associated with these phenomena.

Studies of these dilute gases of weakly interacting ultracold atoms were at the focus of the field in the 1990s after the pioneering observations of Bose-Einstein condensation (*2, 3*). Much of the excitement back then resulted from observations of the macroscopic quantum coherence exhibited by the condensates (*4*). Just as a laser is a coherent source of light, Bose-Einstein condensates behave as coherent sources of matter. Thus, streams of atoms coming out of two condensates display a macroscopic interference pattern similar to that formed by two coherent sources of light.

On the fundamental level, experiments with weakly interacting Bose gases did not lead to big surprises. By and large, they confirmed the theoretical understanding developed in the 1950s and 1960s. However, the simplicity of the system led to new experimental tools that enabled precise control over microscopic parameters. The current trend in the field is to use these tools to alter the strength of interactions between atoms. This can be done, for example, by loading atoms into lattices generated by standing waves of laser light or by trapping atoms in one- or two-dimensional arrangements. If the interactions are strong enough, simple macroscopic coherence may give way to interesting and not yet fully understood many-body states.

The experiment carried out by Donner *et al.* takes a step back to revisit the weakly interacting gas, but now concentrating on the properties just above the transition temperature T_c, where the coherence is not yet truly macroscopic. At this critical stage, bubbles of the coherent condensate exist in the gas as temporary fluctuations that herald the coming of the ordered phase. The size and lifetime of these fluctuations grow without limit at the critical point. In a sense, focusing on the critical regime is another way to amplify the strength of interactions. The modern theory of critical phenomena implies that even weak interactions between individual pairs of particles generate effective interactions between the critical fluctuations that grow in magnitude concomitantly with the size of the fluctuations. Therefore, dynamics at these scales is

The author is in the Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, 76100, Israel. E-mail: altman@wisemail.weizmann.ac.il