Trouble lies ahead for Antarctic ice

It's probably too late to save the West Antarctic glaciers. And East Antarctica's situation is unexpectedly precarious.

Researchers have long recognized that the glaciers of West Antarctica are losing mass: Ice is oozing off the continent and into the sea faster than it's being replaced from above. But the long-term implications have been uncertain. Is the mass loss a short-lived response to the thermal forcing of warmer-than-usual ocean waters? Or will the collapse continue unchecked even if the forcing is removed?

Two widely reported recent papers conclude that the West Antarctic's unstoppable collapse has probably begun. Eric Rignot and colleagues (University of California, Irvine, and NASA's Jet Propulsion Laboratory) document the accelerating glacial retreat in the region shaded in red in figure 1, and they note the lack of any geological features that could restabilize the ice.[1] Ian Joughin and colleagues (University of Washington) used a computer model to simulate the dynamics of the same region; they found that for a wide range of forcing conditions, full-scale collapse of the glaciers is likely to occur over the next several centuries.[2]

Meanwhile, Matthias Mengel and Anders Levermann (Potsdam Institute for Climate Impact Research in Germany) have shown that the larger, thicker, and less dynamic ice sheet of East Antarctica may not be as stable as previously thought.[3] Using new topographic data in conjunction with simulations, they found that the Wilkes Basin, shaded in yellow in figure 1, is held in place by a small volume of coastal ice that could eventually melt. Loss of the East Antarctic ice sheet would have catastrophic consequences for global sea levels over the coming millennia.

Ice-sheet instability

West Antarctica's fragility results from a combination of factors, as sketched in figure 2. First, the ice rests on a bed that lies below sea level. Second, the bed slopes backward, falling deeper below sea level at points farther inland. That setup gives rise to the so-called marine ice-sheet instability, as currents of relatively warm circumpolar deep water eat away at the ice from below.[4]

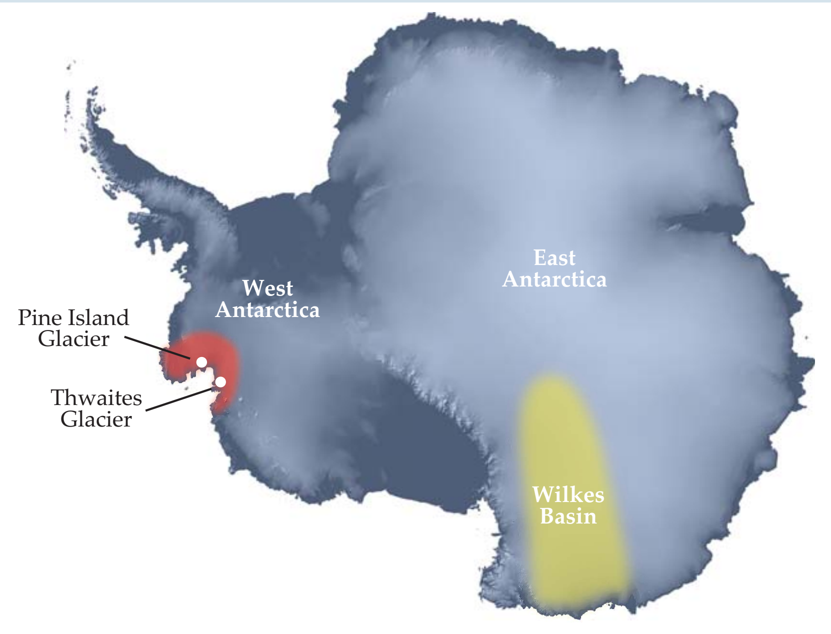

Figure 1. Locations of the Thwaites and Pine Island Glaciers in West Antarctica and the Wilkes Basin in East Antarctica.

When snow falls on a glacier, the ice spreads out under its own weight and slowly flows out to sea. Its dynamics are governed by internal stresses in the ice and friction between the ice and the bedrock. The flux of ice across the grounding line—the outer limit of where the ice contacts the bed—increases rapidly as a function of the thickness of the ice at that location. If a temporary perturbation pushes the grounding line slightly inward, the ice thickness at the grounding line becomes larger. As a result, the discharge from the glacier speeds up, the glacier becomes thinner, and the grounding line retreats farther. The collapse doesn't happen immediately—the ice moves, literally, at a glacial pace—but once started it can be unstoppable.

That simple picture, which suggests that no ice sheet can ever exist on a backward-sloping bed below sea level, doesn't tell the whole story. The shelf of floating ice can, under some circumstances, push back against the grounded ice and help to stem its flow. And the bed is rarely as smoothly sloping as the figure suggests; instead, it's full of hills and bumps that both affect the frictional forces on the ice and can serve as "pinning points," where the bed slopes locally forward and the grounding line can be at least temporarily restabilized.

Tracking topography

It's been known for some time that the marine ice-sheet instability could be at work in West Antarctica. But the complexity of the system made it hard to know for sure. Understanding the dynamics of the region requires good data and good models.

Rignot and colleagues have published extensively on the data side of things. Antarctic topography, above and below the ice, is measured with radar. Grounding lines can be found with surface measurements alone, because the floating ice shelves rise and fall with the tides, whereas grounded ice doesn't. Interferometric synthetic-aperture radar (InSAR)—comparing two phase-sensitive radar maps of a region—reveals the meter-scale vertical tidal motions of the floating ice. (See the Quick Study by Matt Pritchard, PHYSICS TODAY, July 2006, page 68.) The inward limit of that motion marks the grounding line.

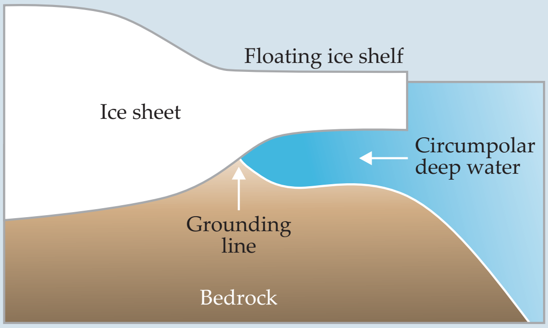

Figure 2. The marine ice-sheet instability arises when ice rests on a bed that lies below sea level and that slopes downward away from the ocean. The rate of ice flow across the grounding line, the outermost point at which the ice contacts the bedrock, depends on the thickness of ice at the grounding line. When a temporary perturbation, such as warmer-than-usual circumpolar deep water, pushes the grounding line back, the rate of discharge increases and the glacier retreats further.

Radar can also penetrate the ice to map the bedrock, but it's not so straightforward. A single radar pulse sent from an airplane or satellite produces a series of reflections: from the ice surface, the bedrock, and features in or below the ice, such as layers of volcanic ash (see PHYSICS TODAY, March 2008, page 17) or subterranean crevasses. Assigning each reflection to the right feature is not always easy.

Rignot and colleagues used 20 years of InSAR data to track the retreat of grounding lines in four West Antarctic glaciers, including Pine Island Glacier and Thwaites Glacier, shown in figure 1. They found that the grounding lines retreated between 10 and 35 km over that time—and that the retreats are speeding up.

Then the researchers compared a published set of bedrock maps[5] (see PHYSICS TODAY, July 2013, page 72) with their own measurements of ice velocities. In a few places, they found that the maps were not consistent, given the necessary constraint of conservation of mass, and that the wrong feature had probably been identified as the bedrock. From their refined bedrock maps, they found that only one of the four glaciers had a significant bedrock bump that could possibly serve as a pinning point. The other three had nothing to stop the grounding-line retreat.

Millennial model

Modeling glaciers, like modeling anything else, is a tradeoff between scope and accuracy. A model can represent a glacier's flow along a single line, or a coarse-grained model can simulate a whole ice sheet. "We used something in between," says Joughin, "a regional-scale model that covered an entire basin, but not the full ice sheet." At that scale, Joughin's team could achieve a spatial resolution of 300 m near the grounding line, and somewhat coarser elsewhere. The model didn't address couplings between glaciers and the atmosphere or ocean, but it did include the rate of melting as an adjustable parameter.

In 2010 Joughin and colleagues applied their model to Pine Island Glacier.[6] They ran simulations for 100 model years under a range of melting conditions and found that regardless of the rate of melting, ice loss continued throughout the whole period. Earlier this year Gaël Durand and colleagues used three different models to simulate the same glacier over 50 model years.[7] They found similar results.

In their latest paper, Joughin and colleagues simulated Thwaites Glacier for 1000 model years. They found that the ice loss not only continued but accelerated. In nearly all of their simulations, the rate of ice loss reached 360 Gt/yr, which would cause a global sea-level rise of 1 mm/yr, before the 1000 years were up. (Right now, Thwaites Glacier is losing about 50 Gt/yr.) That may not sound like much, but it's a signal of worse things to come, including faster grounding-line retreat and the triggering of the collapse of neighboring glaciers within decades. Because simulating those processes was beyond the scope of their model, the researchers stopped their simulations once the threshold of 360 Gt/yr was reached. In the worst case they looked at, it was reached in about 200 years.

Pulling the plug

East Antarctica is many times larger than West Antarctica, but right now it's losing mass at a much smaller rate. Recent maps have revealed, though, that parts of East Antarctica have bedrock topography that's conducive to the same instability plaguing West Antarctica. The Wilkes Basin is one such region.

To simulate the large region, Mengel and Levermann used a relatively coarse model—with 7-km resolution—that they could run for tens of thousands of model years. For the first 200–800 years of each simulation, they introduced a thermal forcing in the ocean to drive melting at the coast. Then they removed the forcing and tracked the basin's evolution for the next 25 000 years. In some simulations, the basin collapsed; in others, it remained intact.

Comparing all their simulations, the pair found that the basin collapsed if and only if a specific chunk of ice—which they termed the "ice plug"—melted during the forcing period. If part or all of the plug remained intact, so did the basin. The plug has a mass of about 30 trillion tons, equivalent to about 80 mm of sea-level rise. "It's a lot of ice," says Levermann, but it pales in comparison to the whole basin—which could raise sea levels by 3 m or more—let alone all of East Antarctica.

Although the simulations required at least 200 years of forcing to melt the plug, there's no guarantee that it couldn't happen faster. If glacial melting altered ocean currents, the water temperature at the grounding line could rise by even more than the 2.5 °C that Mengel and Levermann used in their most extreme simulations. And their model didn't consider the possibility of calving, or ice breaking off in chunks, which could remove parts of the plug even faster.

The models of Thwaites and Pine Island Glaciers and the Wilkes Basin don't explicitly address the effect that those regions' collapse could have in destabilizing neighboring ice, but there must be some impact. As Levermann puts it, "You can't just have a hole in East Antarctica." The entire West Antarctic ice sheet has enough ice to raise sea levels by about 3 m; East Antarctica, more than 50 m. (About two-thirds of East Antarctic ice lies on bedrock above sea level, though, so it's less susceptible to instability.)

The coming sea-level rise will take many generations to play out. Levermann likens the situation to the consequences of nuclear waste: The harm is done on a similar time scale, and although sea-level rise is not as deadly, its effects will be global. Joughin asks, "Is it okay to trigger such an event and leave our great, great grandchildren to take the brunt of it?"

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Ultrafast electron diffraction from an ultracold source

Femtosecond electron bunches extracted from a laser-cooled gas cloud could become a powerful tool for macromolecular studies.

For decades, x-ray and electron diffraction have resolved the atomic-scale details of matter. Extending such techniques to the ultrafast time scales at which chemical reactions occur is a more recent achievement.[1] Thanks to recent advances in accelerator technology this past decade, x rays from free-electron lasers can now probe the structural dynamics of molecules at femtosecond resolution (see PHYSICS TODAY, April 2011, page 13, and for background on FELs the article by William Colson, Erik Johnson, Michael Kelley, and Alan Schwettman, PHYSICS TODAY, January 2002, page 35). And for the past few years, a handful of groups have been working to extend electron sources to that time regime as well—no big-machine physics required. The essential ingredients can all fit on a tabletop.

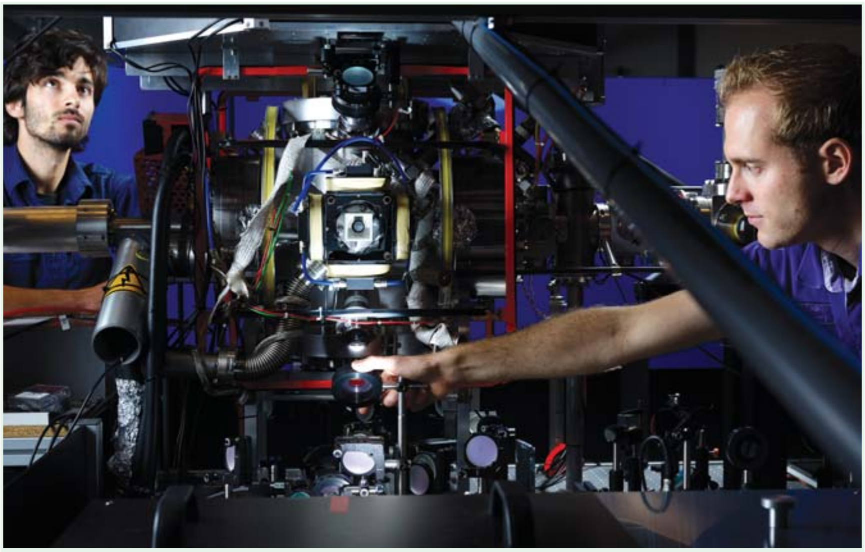

Figure 1. A magneto-optical trap (center) holds an ultracold gas of rubidium atoms that are ionized to generate a 100-fs pulse of electrons. Those electrons are then accelerated and travel to the right in a diffraction experiment. Doctoral students Martin van Mourik (left) and Peter Pasmans (right) adjust the setup. Cooling and trapping laser beams pass from an optical table (foreground) through the quarter-wave plate in Pasmans's hand, and ionization laser pulses are reflected into the trap after passing through the upward-directed black pipe. (Image courtesy of Bart van Overbeeke Fotografie.)

Unlike photons from a laser, though, electrons emitted from a photocathode don't usually hang together well: Thermal drift and Coulomb repulsion spread them apart. And the resulting transverse momentum spread—or, more precisely, its inverse multiplied by Planck's constant, a figure of merit known as the transverse coherence length—determines the sharpness of the Bragg peaks in any electron diffraction experiment.

In 2005 Jom Luiten and his colleagues from Eindhoven University of Technology in the Netherlands proposed a bold scheme to ameliorate the spreading without resorting to apertures, which sacrifice the brightness of a beam. The idea, which his and other groups later implemented, was to liberate bunches of electrons not from a