Startling amounts of ice slipping into the sea have taken glaciologists by surprise; now they fear that this century's greenhouse emissions could be committing the world to a catastrophic sea-level rise

A Worrying Trend of Less Ice, Higher Seas

HAVE AN URGE LATELY TO RUN FOR higher ground? That would be understandable, given all the talk about the world's ice melting into the sea. Kilimanjaro's ice cloak is soon to disappear, the summertime Arctic Ocean could be ice-free by century's end, 11,000-year-old ice shelves around Antarctica are breaking up over the course of weeks, and glaciers there and in Greenland have begun galloping into the sea. All true. And the speeding glaciers, at least, are surely driving up sea level and pushing shorelines inland.

Scientists may not be heading for the hills just yet, but they're increasingly worried. Not about their beach houses being inundated anytime soon; they're worried about what they've missed. Some of the glaciers draining the great ice sheets of Antarctica and Greenland have sped up dramatically, driving up sea level and catching scientists unawares. They don't fully understand what is happening. And if they don't understand what a little warming is doing to the ice sheets today, they reason, what can they say about ice's fate and rising seas in the greenhouse world of the next century or two?

That uncertainty is unsettling. Climatologists know that, as the world warmed in the past, "by some process, ice sheets got smaller," says glaciologist Robert Bindschadler of NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. But "we didn't know the process; I think we're seeing it now. And it's not gradual." Adds geoscientist Michael Oppenheimer of Princeton University, "The time scale for future loss of most of an ice sheet may not be millennia," as glacier models have suggested, "but centuries."

The apparent sensitivity of ice sheets to a warmer world could prove disastrous. The greenhouse gases that people are spewing into the atmosphere this century might guarantee enough warming to destroy the West Antarctic and Greenland ice sheets, says Oppenheimer, possibly as quickly as within several centuries. That would drive up sea level 5 to 10 meters at rates not seen since the end of the last ice age. New Orleans would flood, for good, as would most of South Florida and much of the Netherlands. Rising seas would push half a billion people inland. "This is not an experiment you get to run twice," says Oppenheimer. "I find this all very disturbing."

A rush to the sea

Much of the world's ice may be shrinking under the growing warmth of the past several decades, but some ice losses will have more dramatic effects on sea level than others. Glaciologists worried about rising sea level are keying on the glaciers draining the world's two dominant ice reservoirs, Greenland and Antarctica. Summertime Arctic Ocean ice may be on its way out, but its melting does nothing to increase the volume of ocean water; that ice is already floating in the ocean. The same goes for floating ice shelves around Antarctic. The meltwater from receding mountain glaciers and ice caps is certainly raising sea level, but not much.

The truly disturbing ice news of late is word that some of the ice oozing from the 3-kilometer-thick pile on Greenland has doubled its speed in just the past few years. In the 17 February issue of *Science*, for example, radar scientists Eric Rignot of the Jet Propulsion Laboratory in Pasadena, California, and Pannir Kanagaratnam of the University of Kansas, Lawrence, analyzed observations made between 1996 and 2005 by four satellite-borne radars. These synthetic aperture radars measure the distance to the surface during successive passes over a glacier. The changing distance can then be extracted by letting successive observations form interference patterns. The changing distance, in turn, translates to a velocity of the ice toward the sea.

In central east Greenland, Kangerdlugssuaq Glacier more than doubled its speed from 2000 to 2005, Rignot and Kanagaratnam found, from 6 kilometers per year to 13 kilometers per year. That made it the fastest in Greenland. To the south, Helheim Glacier accelerated 60%. And on the west of Greenland, Jakobshavn Isbrae almost doubled its speed between 1996 and 2005. The accelerations are "actually quite surprising," says glaciologist Julian Dowdeswell of the University of Cambridge in the United

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Published by AAAS

Going. Greenland glaciers like those dumping into Sondre Sermilik Fjord have sped up and retreated.

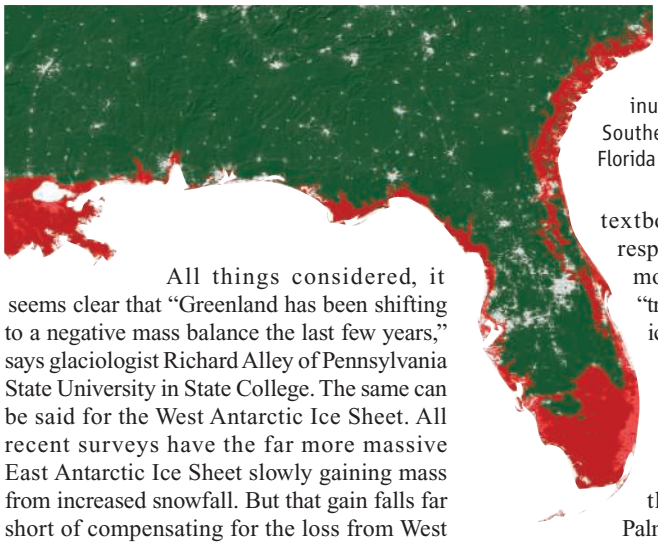
Kingdom. Even at its slower speed, Jakobshavn had ranked as one of the fastest-flowing glaciers in the world, perhaps the fastest; now it's just one of the pack.

As glaciers draining the Greenland Ice Sheet are picking up speed, researchers are realizing that nothing has made up for the increased loss of ice. Greenland's pile of ice is getting smaller. How much smaller is still being debated, if only because of the vast scope of an ice sheet. What goes out through glaciers is just one part of the equation: Ice sheets also lose mass by melting and gain it from snowfall. To gauge those gains and losses, Rignot and Kanagaratnam used previously published estimates of how the warming climate over Greenland has increased meltwater losses and slightly increased snowfall, making for a growing net loss in addition to the glacier flow. All told, the scientists find that the loss of mass from Greenland doubled from 1996 to 2005, reaching 224 ± 41 cubic kilometers per year. Los Angeles uses 1 cubic kilometer of water per year.

In another approach to estimating mass balance, researchers sketch the changing shape and therefore volume of the ice sheet. In a paper just out in the *Journal of Glaciology*, glaciologist Jay Zwally of GSFC and colleagues use satellite radars to measure the height of the Greenland Ice Sheet's broad plateau and airborne laser altimeters to monitor the height of glaciers draining to the coast, which are too small for satellite radars to see reliably. "We have strong evidence the ice sheet was near balance [during] the last decade of the 20th century," says Zwally. "Our measures show a slight positive gain of 11 [cubic kilometers] per year" between 1992 and 2002.

Global warming contrarians have already taken up Zwally's result as evidence that nothing much is happening with the ice sheet, so there's nothing to worry about. Zwally disagrees. "There's no question there's been an acceleration of some of Greenland's glaciers over the last 5 years," after his surveys were completed, he says. "I would say that right now the current loss is 30 to 40 [cubic kilometers] per year," he says, based on his gut feeling about the most recent radar and laser observations.

That's getting close to the mass loss reported last fall using a third approach: repeatedly weighing the ice sheet. Geophysicists Isabella Velicogna and John Wahr of the University of Colorado, Boulder, reported in *Geophysical Research Letters* how the two satellites of the Gravity Recovery and Climate Experiment (GRACE), flying in tandem, gauge the mass beneath them. They precisely measure the changing distance between them caused by the gravitational pull of the passing ice. Between 2002 and 2004, GRACE found a loss of about 82 cubic kilometers of ice per year.



Going under? Global warming might trigger a 6-meter rise in sea level that would inundate coasts (red) worldwide. Southern Louisiana (*left*) and South Florida (*lower right*) would be hard hit.

All things considered, it seems clear that "Greenland has been shifting to a negative mass balance the last few years," says glaciologist Richard Alley of Pennsylvania State University in State College. The same can be said for the West Antarctic Ice Sheet. All recent surveys have the far more massive East Antarctic Ice Sheet slowly gaining mass from increased snowfall. But that gain falls far short of compensating for the loss from West Antarctica. There, Zwally's analysis has the ice shrinking by about 47 cubic kilometers per year. And Velicogna and Wahr, writing in this week's issue of *Science* (p. 1754), report a GRACE-estimated loss of about 148 cubic kilometers per year. In West Antarctica, as in Greenland, the culprit is the acceleration of outlet glaciers in recent years (*Science*, 24 September 2004, p. 1897).

Why the rush?

The recent proliferation of galloping glaciers caught researchers unawares. "None of the models [of glacier flow] predict there should be such rapid change," says glaciologist Ian Joughin of the University of Washington, Seattle (see Perspective on p. 1719). "If you look at a textbook, you'll see an ice sheet response time of 1000 years or more." That's because models "treat ice sheets as a big lump of ice," he says. They melt, or they don't melt.

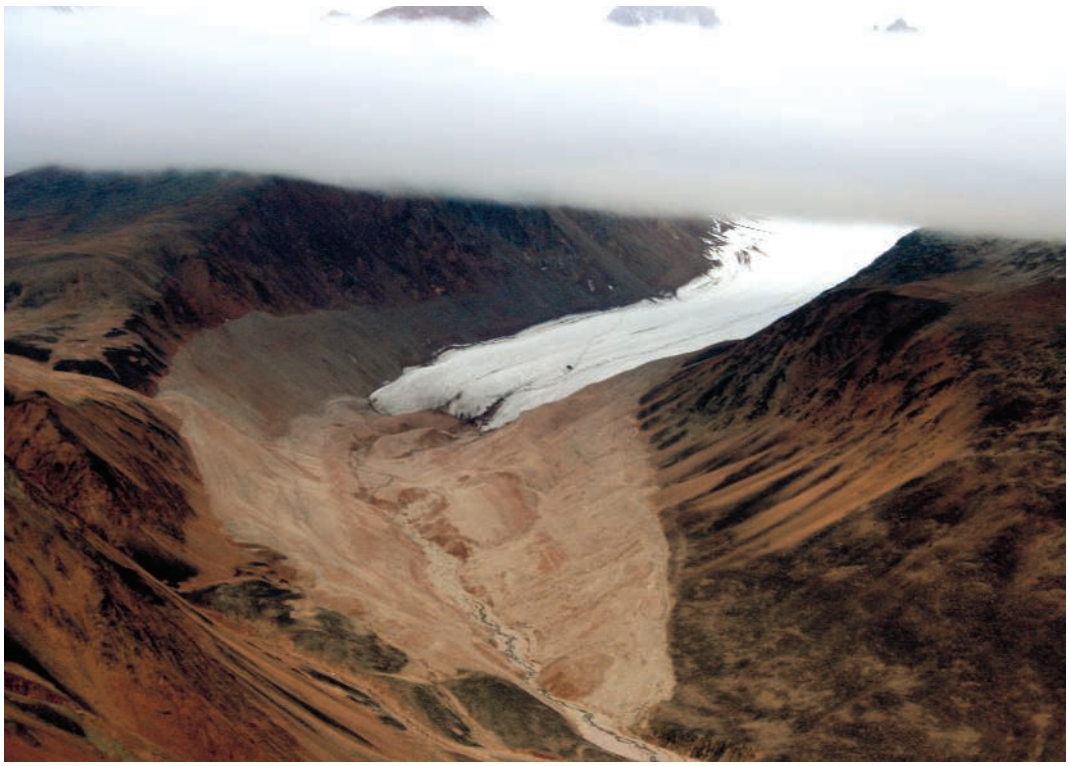
In the case of West Antarctica, there is tentative agreement about what is triggering the acceleration of the glaciers. Around the Palmer Peninsula that juts northward from West Antarctica, the world's strongest regional warming of the past 50 years first puddled the surface of ice shelves with meltwater. The meltwater then drove into the ice along growing cracks, breaking up shelves over a few weeks. Without the shelves to hold them back, apparently, the glaciers feeding them sped up (*Science*, 30 August 2002, p. 1494). To the south, where it's still far too cold for surface melting, a third-of-a-degree warming of the ocean seems to have eaten away at the shelves jutting into the Amundsen Sea. That in turn sped up Pine Island Glacier and its neighbors.

Around Greenland, however, both surface melting and shelf-bottom melting seem to be happening to some extent. Surface melting around the ice sheet's periphery has increased

Off to sea. The acceleration of glaciers draining both the Greenland and Antarctic ice sheets has meant more icebergs and thus more sea-level rise around the world.

CREDITS (TOP TO BOTTOM): IMAGE BY JEREMY L. WEISS AND JONATHAN T. OVERPECK/UNIVERSITY OF ARIZONA; FRANK LUKASSECK/ZEFA/CORBIS

in recent years. Some of the meltwater plunges into open crevasses, where Zwally has shown that it can lubricate the bottom of the ice and accelerate ice flow. But, as Bindschadler argues on page 1720 of this issue of *Science*, the accelerating Greenland glaciers all flow through deep troughs that expose the ice to any warming ocean water, and all lost their buttressing ice shelves before or during acceleration. So both mechanisms are plausible drivers of glacier acceleration, but glaciologists cannot agree on their relative importance.



Not just the heat. Greenland glaciers retreat (tan area) when warming increases melting, but they can also accelerate when warmer ocean water destroys their lower reaches or added meltwater lubricates their undersides.

CREDIT: RICHARD ALLEY

Whither the world's ice

If the recent behavior of ice sheets is not fully understood, their future is largely a blank. "We don't actually understand what's driving these higher velocities," says Dowdeswell, so "it's difficult to say whether that's going to continue," or spread.

At the moment, ice loss from Greenland and West Antarctica combined is contributing less than half of the ongoing 2-millimeters-per-year rise in sea level; the rest comes from melting mountain glaciers and the simple thermal expansion of seawater. If the recent surge of ice to the sea continues, sea level might reach something like half a meter higher by 2100. That would be substantial but not catastrophic. To produce really scary rises really fast (say, a meter or more per century), the air and water will have to continue warming in the right—or wrong—places. The temperature rise will have to spread northward around Greenland and in the south around West Antarctica, reaching the big ice shelves where most of that ice sheet drains. And glacier accelerations triggered near the sea must propagate far inland to draw on the bulk of an ice sheet.

Faced with uncertainty about the present, paleoclimatologists look to the past. About 130,000 years ago, between the last two ice ages, the poles may have warmed as much as they will with only a couple of degrees of global warming. But sea level was considerably higher then, something like 3 to 4 meters higher. In two articles in this issue of *Science*, paleoclimatologist Jonathan Overpeck of the University of Arizona, Tucson (p. 1747), paleoclimate modeler Bette Otto-Bliesner of the National Center for Atmospheric Research in Boulder (p. 1751), and their colleagues consider whether the greenhouse world of a century hence might be as warm—and thus as destructive of ice—as during the previous interglacial.

First they simulated the climate of 130,000 years ago. Back then, Earth was tilted slightly more on its axis, so more solar radiation hit the high northern latitudes, driving warming there. Because the model included that added radiation, it had Greenland warming by about 3°C in the interglacial period. When that warming was put into a model of the ice sheet, the ice melted away slowly (because the model lacked any acceleration mechanisms) until about half remained. That produced enough meltwater to raise sea level 2 to 3 meters. Overpeck and colleagues suggest that another couple of meters of sea level rise could have come from West Antarctica; it was not as warm there, but much of the ice sheet lies below sea level, making it inherently unstable.

When the climate model simulates the next 140 years of rising greenhouse gases, Greenland warms as much by 2100 as it did in the previous interglacial and would thus—eventually—melt as much. "Ice sheets have contributed meters above modern sea level in response to modest warming," Overpeck and his colleagues conclude, and "a threshold triggering many meters of sea-level rise could be crossed well before the end of this century."

The paleoclimate argument for large, imminent ice losses "is fascinating and scary at the same time," says Oppenheimer. "Paleoclimate always has a large amount of uncertainty, [but] we should take this as a serious warning sign. You could lock in a dangerous warming during this century."

An icy conundrum

The ice sheet problem today very much resembles the ozone problem of the early 1980s, before researchers recognized the Antarctic ozone hole, Oppenheimer and Alley have written. The stakes are high in both cases, and the uncertainties are large. Chemists had shown that chlorine gas would, in theory, destroy ozone, but no ozone destruction had yet been seen in the atmosphere. While the magnitude of the problem remained uncertain, only a few countries restricted the use of chlorofluorocarbons, mainly by banning their use in aerosol sprays.

But then the ozone hole showed up, and scientists soon realized a second, far more powerful loss mechanism was operating in the stratosphere; the solid surfaces of ice cloud particles were accelerating the destruction of ozone by chlorine. Far more drastic measures than banning aerosols would be required to handle the problem.

Now glaciologists have a second mechanism for the loss of ice: accelerated flow of the ice itself, not just its meltwater, to the sea. "In the end, ice dynamics is going to win out" over simple, slower melting, says Bindschadler. Is glacier acceleration the ozone hole of sea level rise? No one knows. No one knows whether the exceptionally strong warmings around the ice will continue apace, whether the ice accelerations of recent years will slow as the ice sheets adjust to the new warmth, or whether more glaciers will fall prey to the warmth. No one knows, yet.

–RICHARD A. KERR