On Thin Ice?

How soon humanity will have to move inland to escape rising seas depends in great part on how quickly West Antarctica's massive ice sheet shrinks. Scientists are finally beginning to agree on what controls the size of the sheet and its rate of disintegration

BY ROBERT A. BINDSCHADLER AND CHARLES R. BENTLEY

GARY BRAASCH

COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.

DISINTEGRATION OF ICE along Antarctica's coasts is replenished by snowfall farther inland. Scientists sound an alarm when they find evidence that ice is being lost faster than it is accumulating.

COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.

Twelve thousand years ago, as the earth emerged from the last ice age,

vast armadas of *Titanic*-size icebergs invaded the North Atlantic. Purged vigorously from the enormous ice sheets that smothered half of North America and Europe at the time, those icebergs displaced enough water to raise global sea level more than a meter a year for decades.

As the frozen north melted, the ice gripping the planet's southernmost continent remained essentially intact and now represents 90 percent of the earth's solid water. But dozens of scientific studies conducted over the past 30 years have warned that the ice blanketing West Antarctica—the part lying mainly in the Western Hemisphere—could repeat the dramatic acts of its northern cousins. Holding more than three million cubic kilometers of freshwater in its frozen clutches, this ice sheet would raise global sea level five meters (about 16 feet) if it were to disintegrate completely, swamping myriad coastal lowlands and forcing many of their two billion inhabitants to retreat inland.

Most Antarctic scientists have long concurred that the continent's ice has shrunk in the past, contributing to a rise in sea level that continued even after the northern ice sheets were gone. The experts also agree that the ice covering the eastern side of the continent is remarkably stable relative to that in West Antarctica, where critical differences in the underlying terrain make it inherently more erratic. But until quite recently, they disagreed over the likelihood of a catastrophic breakup of the western ice sheet in the near future. Many, including one of us (Bindschadler), worried that streams of ice flowing from the continent's interior toward the Ross Sea might undermine the sheet's integrity, leading to its total collapse in a few centuries or less. Others (including Bentley) pointed to the sheet's recent persistence, concluding that the sheet is reasonably stable.

For a time it seemed the debate might never be resolved. Agreement was hampered by scant data and the challenge of studying a continent shrouded half the year in frigid darkness. In addition, although areas of the ice sheet have drained quickly in the past, it is difficult to determine whether changes in the size or speed of the ice seen today are a reflection of normal variability or the start of a dangerous trend. In the past few years, though, a variety of field and laboratory studies have yielded a growing consensus on the forces controlling West Antarctica's future, leading experts in both camps to conclude that the ice streams pointing toward the Ross Sea are not currently as threatening as some of us had feared.

We remain puzzled, however, over the ice sheet's ultimate fate. New studies have revealed thinning ice in a long-neglected sector of West Antarctica, suggesting that a destructive process other than ice streams is operating there. And another region—the peninsula that forms Antarctica's northernmost arm—has recently experienced warmer summer temperatures that are almost certainly the reason behind an ongoing breakup of ice along its coasts.

Around the world temperatures have risen gradually since the end of the last ice age, but the trend has accelerated markedly since the mid-1990s with the increase of heat-trapping greenhouse gases in the atmosphere. So far the peninsula seems to be the only part of Antarctica where this recent climate trend has left its mark; average temperatures elsewhere have risen less or even cooled slightly in the past 50 years. Researchers are now scrambling to determine whether global warming is poised to gain a broader foothold at the bottom of the world.

Overview/*Antarctic Ice*

- For nearly three decades, numerous Antarctic experts warned that West Antarctica's ice sheet is in the midst of a rapid disintegration that could raise global sea level five meters in a few centuries or less.
- Many of those researchers now think that the ice sheet is shrinking much more slowly than they originally suspected and that sea level is more likely to rise half a meter or less in the next century.
- That consensus is not without its caveats. The ice sheet's poorly understood Amundsen sector now appears to be shrinking faster than previously thought.
- Global warming, which has so far played a negligible role in West Antarctica's fate, is bound to wield greater influence in the future.

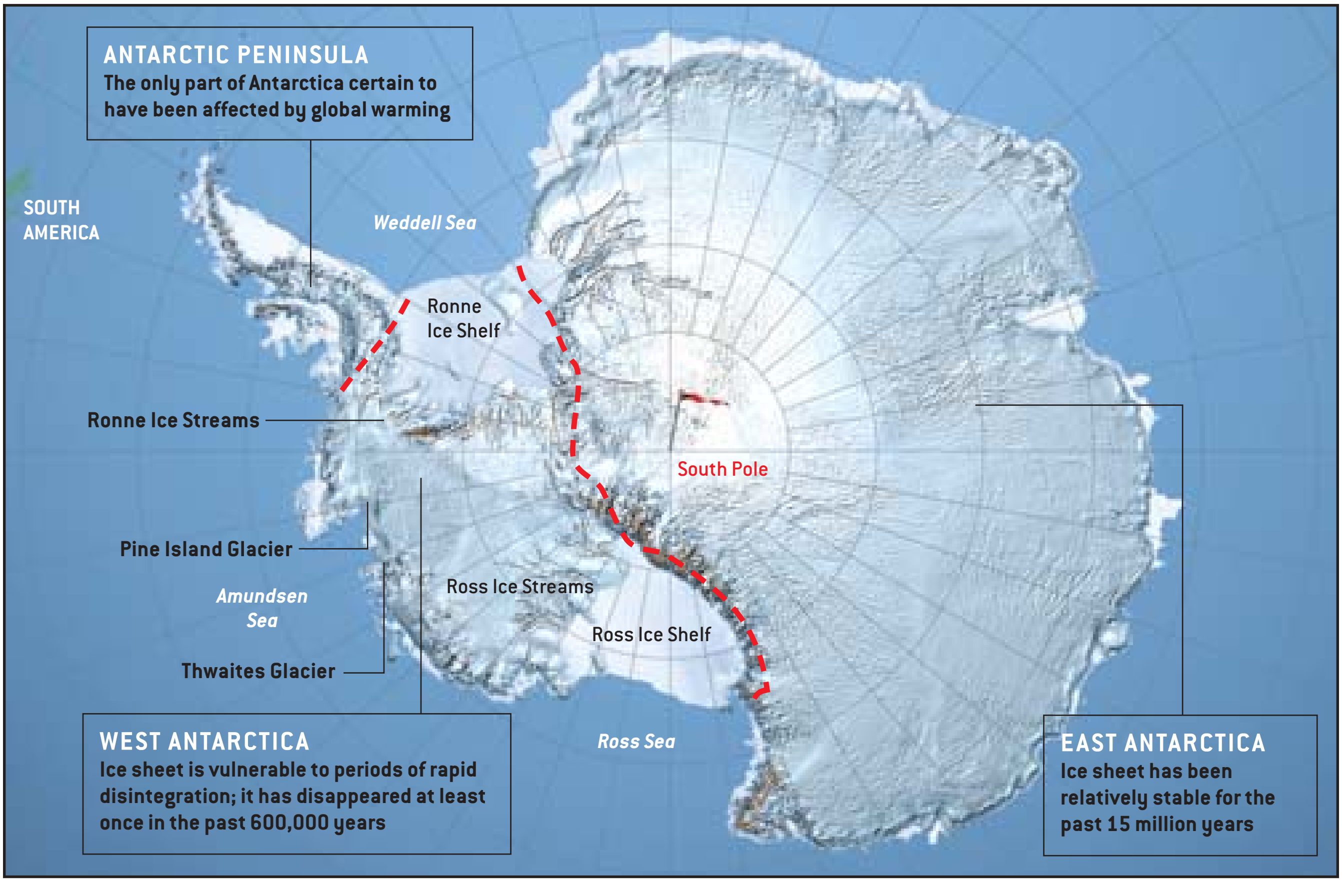
Early Alarms

INDICATIONS THAT the West Antarctic ice sheet might be in the midst of a vanishing act first began cropping up about 30 years ago. In 1974 Johannes Weert-

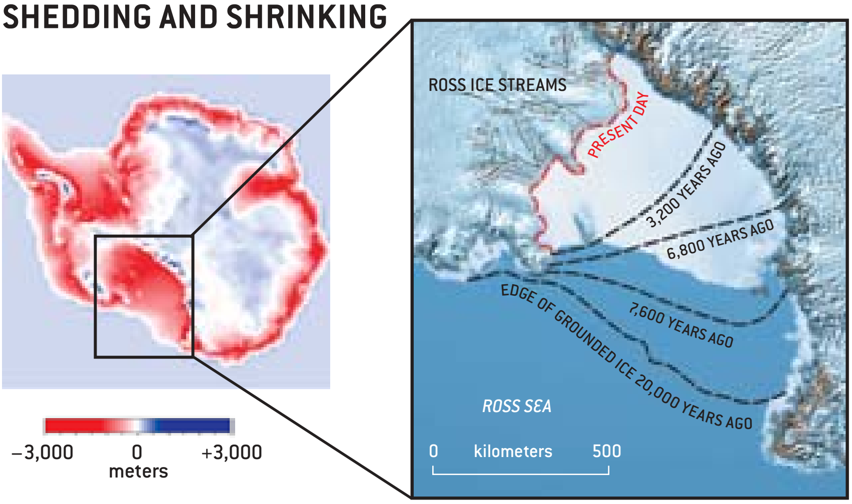
COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.

PAST, PRESENT AND FUTURE?

ANTARCTICA'S THICK BLANKET OF ICE (*below*) has been contracting, mostly gradually but sometimes swiftly, since the height of the last ice age, 20,000 years ago. The greatest reduction has occurred in West Antarctica, where the ice sheet is considerably more fragile than its counterpart in the east. Because the western sheet has changed quickly in the past, scientists have been unsure whether recent dramatic ice losses reflect normal variability or the start of an ominous trend toward total collapse. In the wake of a catastrophic collapse, rapidly rising seas would flood coastal communities around the world. —*R.A.B. and C.R.B.*

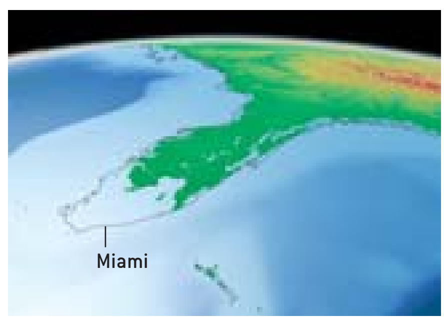


SHEDDING AND SHRINKING



CHANGE IN ICE THICKNESS since the last ice age (*above left*) translates into a loss (*red*) of about 5.3 million cubic kilometers, much of it from West Antarctica. The ice sheet's grounded edge, that reaching the seafloor, has shrunk particularly rapidly in the Ross Sea (*detail, right*) over the past 7,000 years, retreating some 700 kilometers inland.

THE WORST-CASE SCENARIO



COMPLETE COLLAPSE of West Antarctica's ice sheet would raise sea level five meters. Among the casualties would be southern Florida (*above*), where about a third of the famous peninsula would disappear underwater. Today West Antarctica contributes about 10 percent of the average sea-level rise of two millimeters a year.

DAVID FIERSTEIN (*main Antarctica map and Ross Ice Shelf map*); ROBERT A. BINDSCHADLER (*ice thickness map*); WILLIAM F. HAXBY (*Florida map*)

COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.

Chilly Realities

PREDICTING ANTARCTIC ICE SHEETS' response to changing climate and their influence on sea level is not always straightforward. Here are a few of the less obvious phenomena that scientists must take into account:

Ice need not melt to add to rising seas

Ice that was once on land contributes to global sea level as soon as it begins floating. Indeed, an iceberg—most of which sits below the ocean surface—is already displacing as much seawater as it will in liquid form. The same is true for ice shelves, the floating tongues of ice that extend seaward from the edges of continents. In Antarctica, frigid temperatures—averaging about –34 degrees Celsius (–29 degrees Fahrenheit)—mean that very little of that continent's ice ever melts. That might change if global warming becomes more pervasive in the region, but at present Antarctica influences sea level only when solid ice, which is delivered to the coasts by coastal glaciers or by other natural conveyor belts called ice streams, breaks off or adds to existing ice shelves.

FLOATING ICEBERG belies its true size when viewed from above. Ninety percent of its mass lurks below the surface.

Ice can either accelerate or counteract the effects of global warming

Think of a snowy field in the bright sun. Ice and snow reflect much more solar energy back to space than dark oceans and land surfaces do. Such reflection tends to enable an already cold part of the atmosphere above the ice to stay cool, increasing the likelihood that more ice will form.

On the other hand, if global warming heats the atmosphere enough to begin melting the ice and exposing more of the darker surface below, then the region will absorb more solar energy and the air will become warmer still.

Global warming could either slow the rise of sea level or speed it up

Warmer air increases evaporation from the oceans and carries more moisture than cooler air does. So as global warming increases, more evaporated seawater from temperate areas could be transported to polar areas, where it would fall as snow. This process would be further enhanced if global warming were to melt significant amounts of sea ice and expose more of the ocean surface to the atmosphere. All else being equal, ocean water could be preserved as snow faster than it would reenter the sea, alleviating some of the rise in sea level. The catch is that global warming can also cause land ice to melt or break apart more quickly. The ultimate effect of global warming on ice sheets depends on which process dominates.

—R.A.B. and C.R.B.

man of Northwestern University published one of the most influential early studies, a theoretical analysis of West Antarctica based on the forces then thought to control the stability of ice sheets. By that time scientists were well aware that most of the land underlying the thick ice in West Antarctica sits far below sea level and once constituted the floor of an ocean. If all the ice were to become liquid, a mountainous landscape would appear, with valleys dipping more than two kilometers below the surface of the sea and peaks climbing two kilometers above it. Because the boundaries of West Antarctica are so sunken, ice at the edges makes extensive contact with the surrounding seawater, and a good deal extends—as floating ice shelves—onto the ocean surface.

Weertman's troubling conclusion was that any ice sheet that fills a marine basin is inherently unstable when global sea level is on the rise, which most scientists agree has been the case for the past 20,000 years. This instability arises because the edges of a marine ice sheet can be easily stressed or even lifted off the underlying sediment by the natural buoyant effects of water. (In contrast, the ice sheet in East Antarctica sits on a continent, most of which rests high above the deleterious influence of the sea.) The outcome of Weertman's simple calculation was that West Antarctica's ice sheet was on a course toward total collapse. Nothing short of a new ice age could alter this fate.

If Weertman's thinking was correct, it meant that the modern ice sheet was already a shrunken version of its former self. Many early discoveries lent support to this conclusion. Explorers found unusual piles of rock and debris (which only moving ice could have created) on mountain slopes high above the present surface of the ice, indicating that the ice was once much thicker. Likewise, deep gouges carved in the seafloor off the coast implied that the grounded edge of the ice sheet (the part resting on the seafloor) once extended farther out into the ocean [*see box on preceding page*]. Based on these kinds of limited observations, some researchers estimated that the ice sheet was originally as much as three times its

DAVID FIERSTEIN

COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.

present volume and that it was shrinking fairly slowly—at a rate that would lead to its complete disappearance in another 4,000 to 7,000 years.

The idea that West Antarctica could lurch much more rapidly toward collapse was not formulated until researchers started paying close attention to ice streams—natural conveyor belts hundreds of kilometers long and dozens of kilometers wide. Early investigators inferred that these streams owe their existence in part to tectonic forces that are pulling West Antarctica apart, thinning the crust and allowing an above-average amount of the earth's internal heat to escape. This extra warmth from below could melt the base of the ice sheet, providing a lubricated layer that would allow the ice to move rapidly down even the gentlest of slopes. Indeed, airborne surveys using ice-penetrating radar revealed in the 1970s that two networks of ice streams drain ice from the continent's interior and feed it to West Antarctica's two largest ice shelves, the Ross and the Ronne. As the ice reaches the seaward edge of these shelves, it eventually calves off as huge icebergs. As this dynamic picture of ice streams came to light, so did the first warnings that they harbored the potential to drain the entire ice sheet in a few centuries or less.

Streams of Uncertainty

DRIVEN BY THE NEW knowledge that the fate of the West Antarctic ice sheet would depend strongly on how fast these streams were removing ice from the continent, teams from NASA, Ohio State University and the University of Wisconsin–Madison set up summer research camps on and near the ice streams in 1983. Some scientists probed the interior of the streams with radar and seismic explosions; others measured their motion and deformation at the surface. They quickly found that these immense rivers race along at glaciologically breakneck speeds—at hundreds of meters a year, many times faster than the average mountain glacier.

Different field investigators sought explanations for the speed of the streams by melting narrow, kilometer-long holes through the ice to extract samples of the ancient seafloor below. Ground-up shells of marine organisms mixed with pebbles, clay and eroded rock, deposited there over many millennia, now form a bed of muddy paste that is so soft and well lubricated that the ice streams can glide along even more easily than earlier researchers expected. If they had instead found crystalline rock, like that underlying most continental ice sheets, including East Antarctica's, they would have concluded that the greater friction of that material had been inhibiting ice motion.

These realizations left wide open the possibility of swift drainage along the Ross ice streams. In contrast, British workers who were studying the Ronne ice streams on the other side of West Antarctica reassured the world that the prospects were not nearly so grim in their sector. But the scientists camped out near the Ross Ice Shelf had reason to believe that once the Ross ice streams carried away that region's one million cubic kilometers of ice, the rest of the sheet—including the area drained by the Ronne streams and part of the East Antarctic ice sheet—would surely follow.

In the 1990s researchers began to notice another potentially unsettling characteristic of the Ross ice streams: they are not only fast but fickle. Radar examinations of the hidden structure below the surface of the grounded ice revealed that the ice streams were not always in their present locations. Satellite imagery of the Ross Ice Shelf, which is composed of ice that has arrived over the past 1,000 years, discovered crevasses and other features that serve as a natural record of dramatic and unmistakable changes in the streams' rates of flow. Indeed, one stream known simply as "C" apparently stopped flowing suddenly a century and a half ago. Similarly, the Whillans ice stream has been decelerating over the past few decades. If the streams do come and go, as such findings implied, then their future would be much more difficult to predict than once assumed. The most alarming possibility was that the stagnant streams might start flowing again without warning. But reassurance against that prospect, at least for the near future, was soon to come.

About five years ago a slew of reports began providing key evidence that the ice sheet may not have thinned as much as previously estimated. In 2000 Eric J. Steig of the University of Washington used new techniques to analyze an old ice core recovered in 1968 from the heart of West Antarctica. The initial analysis had indicated that the ice was 950 meters higher during the last ice age than it is today, but Steig's improved interpretation reduced

Even if not sustained, regional collapse may have occurred during brief periods and could happen again.

GARY BRAASCH

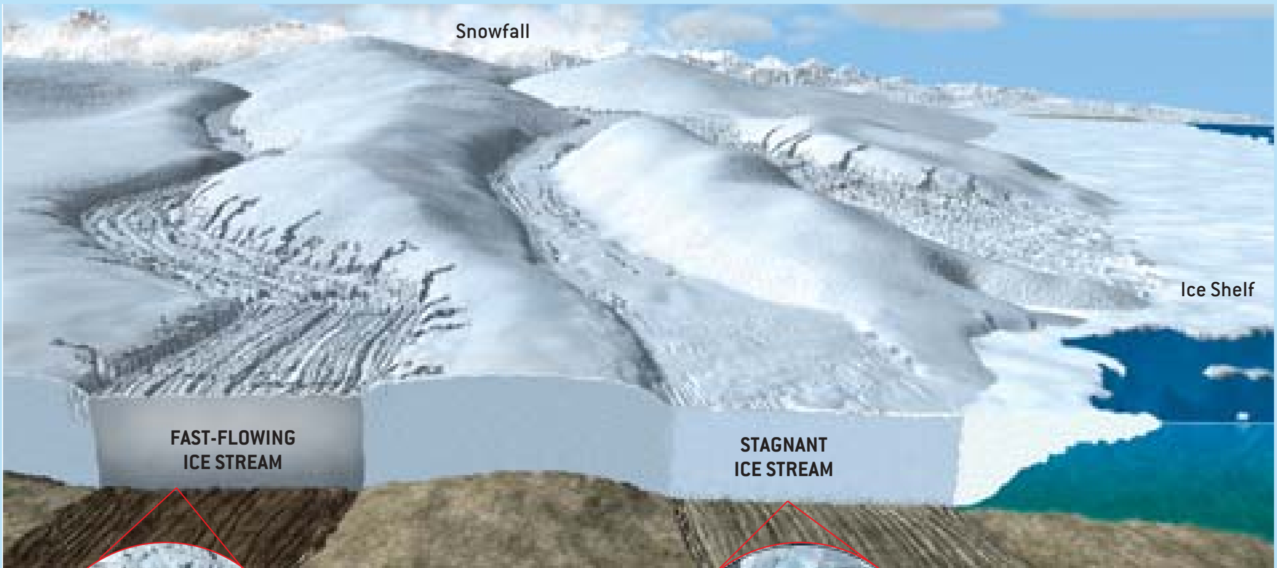
THE AUTHORS

ROBERT A. BINDSCHADLER and CHARLES R. BENTLEY have devoted most of their research careers to investigating the West Antarctic ice sheet and the continent below it. In 23 years at the NASA Goddard Space Flight Center, Bindschadler has led 12 field expeditions to the frozen land down under. Now a senior research fellow at Goddard, he has developed numerous remote-sensing technologies for glaciological application—measuring ice velocity and elevation using satellite imagery and monitoring melting of the ice sheet by microwave emissions, to name just two. Bentley's first visit to West Antarctica lasted 25 months, during which he led an exploratory traverse of the ice sheet as part of the 1957–58 International Geophysical Year expedition. He returned regularly as a member of the geophysics faculty at the University of Wisconsin–Madison until his retirement in 1998.

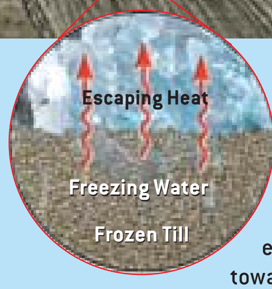
COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.

SLIP SLIDING AWAY

IMMENSE ICE STREAMS shuttle ice to West Antarctica's coasts at speeds of hundreds of meters a year, feeding more than 400 cubic kilometers to ice shelves annually. They could thus drain the ice sheet in 7,000 years or less if snowfall did not replenish it. Reassuring findings indicate, however, that the streams can stagnate for long periods. Whether they stop or go depends on how much liquid water exists at the base of the ice: a lot makes a stream move quickly; too little slows it down. *—R.A.B. and C.R.B.*



ICE STREAMS GLIDE swiftly when the muddy till below them becomes wet. Water forms when the earth's internal heat warms the bottom of the ice. Because the thick overlying ice insulates the deeper layers from the cold atmosphere, the till becomes warm enough to melt the base of the stream. Meltwater then seeps into the till, which becomes extremely soft and smears easily under the weight of the overlying ice.



ICE STREAMS STAGNATE suddenly when water becomes scarce. As ice flows rapidly, it thins, allowing the frigidity of the air to penetrate it more deeply. As the ice closer to the till cools, the earth's heat escapes more quickly toward the surface and has no time to melt ice at the base. This heat loss freezes the water in the till, making it stiff and sticky. Unless water from upstream keeps the till pliable, the stream grinds to a halt.

DAVID FIERSTEIN

that difference to 200 meters. In the mountains of the Executive Committee Range, John O. Stone, another University of Washington researcher, clocked the thinning of the ice sheet by measuring the radioactive by-products of cosmic rays, which have decayed at a known rate since the moment when ice retreat left rock outcrops freshly exposed. These observations put severe limits on the original size of the ice sheet, suggesting that it could have been no more than two and a half times as large as it is today.

By early 2001 scientists on both sides of the debate over the future of West Antarctica's ice sheet were still able to maintain their points of view. Reconciling solid but contradictory evidence required everyone to recognize that great variability on shorter timescales can also appear as lesser variability on longer timescales. Since then, improved measurements of the motion of the Ross ice streams have confirmed that new snowfall is generally keeping pace with ice loss in this sector, meaning that almost no overall shrinkage is occurring at present. And by late 2001 most Antarctic scientists—including both of us—could finally agree that the Ross ice streams are *not* causing the ice to thin at this time. Variations in snowfall versus ice discharge over the past millennium seem to have averaged out—a sign that the ice sheet is less likely to make sudden additions to rising seas than some investigators had expected.

But scientists engaged in this debate know all too well that the dynamic nature of the ice streams dictates that this reconciliation explains only what is going on today. Looking further back in time, for instance, geologic evidence near the U.S. McMurdo Station suggests that the ice sheet retreated through that area very rapidly around 7,000 years ago. Thus, even if not sustained, this type of regional collapse may have occurred during brief periods and could happen again.

To gain a better handle on the future stability of the ice sheet, researchers have also developed a firmer understanding of the forces that control the flow of ice within streams, including an explanation for why the streams can stop, start and change velocity on different timescales [*see box above*]. It turns out that sediment (also called till) and water in the seabed

COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.

are in control over days and years, but global climate, principally through air temperature and sea level, dominates over millennia. This and other new information will make it possible to build more reliable computer models of how the streams might behave centuries hence.

Weak Underbelly Exposed

THAT THE AREA of the West Antarctic ice sheet drained by the Ross ice streams is in less danger of imminent collapse is good news. But in the past couple of years it has become clear that not all sections of West Antarctica behave in the same way.

So far the ice sheet's own dynamics have exerted enough control over its size to avoid a swift demise.

While field-workers were concentrating their efforts on the ice streams feeding the Ross and Ronne ice shelves, several satellite sensors were patiently collecting data from another sector of the ice sheet, the poorly understood region adjacent to the Amundsen Sea. There groups from the U.S. and Great Britain have discovered that the glaciers in this mysterious area are disappearing at an even faster rate than had been originally hypothesized for the Ross ice streams.

After poring over millions of ice-elevation measurements made from space during the 1980s and 1990s, Duncan J. Wingham of University College London and H. Jay Zwally of the NASA Goddard Space Flight Center showed independently that the parts of the ice sheet that feed the Pine Island and Thwaites glaciers are thinning, the latter at more than 10 centimeters a year. These results mesh beautifully with another recent report, by Eric Rignot of the Jet Propulsion Laboratory in Pasadena, Calif. Using radar interferometry, a technique capable of detecting ice movement as small as a few millimeters, Rignot observed that both glaciers are delivering ice increasingly quickly to the Amundsen Sea *and* shrinking toward the continent's interior. As a result, they currently contribute between 0.1 and 0.2 millimeter a year to global sea-level rise—up to 10 percent of the total. At that rate these glaciers would drain 30 percent of the total ice sheet in 7,500 to 15,000 years, or much faster if a catastrophe like the one hypothesized earlier for the Ross sector were to occur.

This new evidence is no surprise to glaciologists such as Terence J. Hughes of the University of Maine, who long ago dubbed the Amundsen sector "the weak underbelly of the West Antarctic ice sheet." But logistical limitations have discouraged field observations in this remote region for decades—it is far from any permanent research station and is renowned as one of the cloudiest regions on the earth. In addition, unique qualities of the Amundsen Sea glaciers may mean that the hard-won knowledge from the Ross sector will be inapplicable there. The surfaces of the glaciers slope more steeply toward the sea than do the ice streams, for example. And because the glaciers dump their ice directly into the sea instead of adding ice to an existing ice shelf, some scientists have argued that this region may be further along in the disintegration process than any other part of Antarctica.

Turning Up the Heat

UNCERTAINTY OVER the vulnerability of the Amundsen Sea sector is but one of several unknowns that scientists still must address. Increasing temperatures related to global warming could begin creeping toward the South Pole from the Antarctic Peninsula, where the summertime atmosphere has already warmed by more than two degrees C since the 1950s. Even seemingly subtle changes in air temperature could trigger disintegration of ice shelves that are relatively stable at present. Evidence reported this year also suggests that warmer ocean waters mixing from lower latitudes may be melting the ice sheet's grounded edges faster than previously assumed, along with reducing the amount of ice in the Amundsen Sea.

Conveniently for those of us living in the world today, the West Antarctic ice sheet appears to possess more helpful feedbacks—such as those that can cause fast-moving ice streams to stagnate for centuries on end—than either its North American or European cousins long gone. Their destruction occurred suddenly as a result of a few degrees of warming, and yet much of West Antarctica's ice survived. Weertman's early model seems to have oversimplified the ice sheet's own dynamics, which so far have exerted enough control over its size to avoid, or at least forestall, a swift demise.

Based on what we know so far, we predict—albeit cautiously—that the ice sheet will continue shrinking, but only over thousands of years. If that is correct, West Antarctica's average effect on sea level could be roughly double its historic contribution of two millimeters a year. That means this ice sheet would add another meter to sea level only every 500 years. But before anyone breathes a sigh of relief, we must remember that this remarkable ice sheet has been surprising researchers for more than 30 years—and could have more shocks in store. SA

GARY BRAASCH

MORE TO EXPLORE

Rapid Sea-Level Rise Soon from West Antarctic Ice-Sheet Collapse? Charles R. Bentley in *Science*, Vol. 275, pages 1077–1078; February 21, 1997.

Future of the West Antarctic Ice Sheet. Robert Bindschadler in *Science*, Vol. 282, pages 428–429; October 16, 1998.

The West Antarctic Ice Sheet: Behavior and Environment. Edited by Richard B. Alley and Robert A. Bindschadler. Antarctic Research Series, Vol. 77. American Geophysical Union, 2001.

West Antarctic research program Web site: **www.glacier.rice.edu/**

COPYRIGHT 2002 SCIENTIFIC AMERICAN, INC.