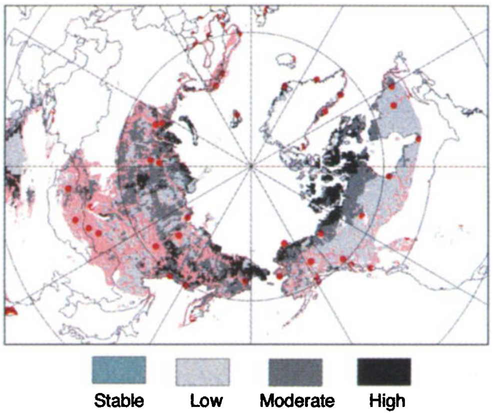
sons. Its Arctic territory supports a much larger population than do other permafrost-laden regions. And whereas Arctic architects in North America have tended to favor wood, their Soviet counterparts generally opted for concrete or brick edifices that pushed pilings to the limit, says geologist Peter Williams of Carleton University in Ottawa. So far, thawing permafrost has damaged roughly 300 apartment buildings in the Siberian cities of Norilsk and Yakutsk alone.

The situation, it appears, will only become direr. Lev Khrustalev, a geocryologist at Moscow State University, analyzed potential failures of five-story apartment buildings in the Russian Arctic as warmer temperatures reduce the ground's ability to bear weight. Assuming that the region continues to warm at the modest rate of 0.075°C per year, Khrustalev estimates that by 2030, *all* five-story structures built between 1950 and 1990 in Yakutsk, a city of 193,000 people, could come crashing down unless steps are taken to strengthen them and preserve the permafrost. Khrustalev has called repeatedly for modifications of Russian building codes to account for warming, to no avail.

The highest priority, experts say, is to come to grips with ice-rich permafrost, which is the type most prone to thawing. One strategy being floated is to preempt nature and thaw patches of this permafrost before construction starts. But this approach is unlikely to be adopted by many builders, Osterkamp says, as it could delay projects by up to 5 years. Some Arctic communities are already implementing less radical solutions, such as putting buildings on screw jacks or latticelike foundations that can be adjusted easily to accommodate shifting ground.



Danger zones. This map shows which towns and centers (red) and smaller settlements (pink) are most threatened by thawing permafrost.

To help planners identify settlements that need urgent action, experts are working up hazard maps based on permafrost type and warming models. "What we see now will only get worse. We need increased vigilance," says geologist Stephen Robinson of St. Lawrence University in Canton, New York. Robinson, Réjean Couture of the Geological Survey of Canada in Ottawa, and colleagues have worked with two Canadian Arctic towns, Norman Wells and Tuktoyaktuk, to tackle current problems and forecast future ones. Other hazard maps developed by Frederick Nelson's group at the University of Delaware, Newark, and Oleg Anisimov of the State Hydrological Institute in St. Petersburg, Russia, warn of trouble for places such as Barrow, Alaska; Inuvik, Northwest Territories; and Yakutsk, Norilsk, and Vorkuta in Russia.

According to geologist Rostislav Kamensky of the Permafrost Institute in Yakutsk, which will host a conference on permafrost engineering next month, sustainable development in the High Arctic depends on finding ways to adapt to thawing permafrost—not to mention shoring up the existing infrastructure before the next collapse catches people unawares. —**ERICA GOLDMAN**

With reporting by Julia Day in Cambridge, U.K.

NEWS

Breaking Up Is Far Too Easy

Spring is in the air on the Antarctic Peninsula, where rising temperatures are eroding ice shelves that have been in place for millennia. Their retreat could augur a far more perilous melting of the mainland ice sheets

MARGUERITE BAY, ANTARCTICA—As freezing rain pelts the deck of the *RRS James Clark Ross*, half a dozen men gather around as a winch hauls a 6-meter-tall, spindly steel contraption from the gray-green swells. A few minutes later the mackintosh-clad figures retrieve a cylinder from the clutches of the orange rig, then use a piston to extrude a clear plastic tube filled with grainy sediment. Two postdocs slice the tube into 1-meter sections, score each lengthwise with a saw, and carry the pieces below deck. There, on a steel workbench, they split the top section's soft mass with a wire, as though cutting cheese.

"This is the last 10,000 years," Cambridge University glaciologist Julian Dowdeswell says, pointing to a top section of oozing, greenish sludge. Delving further back in time, Dowdeswell presses his fingertips into stiff, dark-gray mud lower in the sediment core. It looks and feels like the kind of stuff one might slather on at a spa, but to scientists, it's vastly more precious: The mud is loaded with grains of sand and other glacial debris deposited by an ice sheet that covered this bay 15,000 years ago. These sediments hold clues to the climatic history of Antarctica—and, perhaps, to its future.

Catch of the day. Postdocs Colm O'Cofaigh and Jeffrey Evans split a plug of sediment fresh from the sea floor off the Antarctic Peninsula.

Collecting mud cores in this part of the world is no pleasure cruise. The *James Clark Ross*, a British Antarctic Survey (BAS) ship, spent a nauseating 2 days crossing the stormy Drake Passage that separates the peninsula and Cape Horn at the tip of South America. Here in Marguerite Bay, Dowdeswell, BAS marine geologist Carol Pudsey, and their queasy coring crew are pulling 12-hour shifts under bleak skies, cheered on by a few curious petrels and albatrosses. The discomfort is a small price to pay to gather data that could help unravel the profound environmental changes now transforming the Antarctic Peninsula. "This is a scientific problem that's really relevant to climate change," says Pudsey. "You can only gather the data by going there."

Call it the mystery of the disappearing ice. The past dozen austral summers have witnessed titanic breakups of the peninsula's ice shelves, the massive, floating plates that gird the peninsula's flanks. During the BAS cruise last February, a slab of ice the size of Rhode Island started fissioning into fleets of icebergs. The disintegration of much of the Larsen B ice shelf on the peninsula's east side in a mere 5 weeks was "the largest event of its kind" since satellites began to record the ice shelves breaking up 30 years ago, says glaciologist Ted Scambos of the University of Colorado, Boulder. Warming is clearly the culprit, he and oth-

CREDITS: (TOP TO BOTTOM) F. E. NELSON *ET AL., NATURE* 410, 889 (2001); J. KAISER ers say. In the peninsula region over the past half-century, the mercury has risen five times faster than the global average.

The mystery lies in what the breakup portends. Sediment cores have begun to yield provocative insights, some suggesting that the ice shelves are suffering unprecedented losses since the last ice age ended 11,000 years ago. Other cores, however, indicate that parts of this region saw warmer days. What is happening now, therefore, could be part of a natural cycle, perhaps exacerbated by greenhouse warming.

Whatever the cause, if the warming trend continues, the peninsula itself might soon lose most of its ice shelves, exposing a rocky shoreline to the sea. The rest of the world is unlikely to notice the change: Because the floating shelves displace as much water as they would shed through melting, their melting would not raise global sea levels.

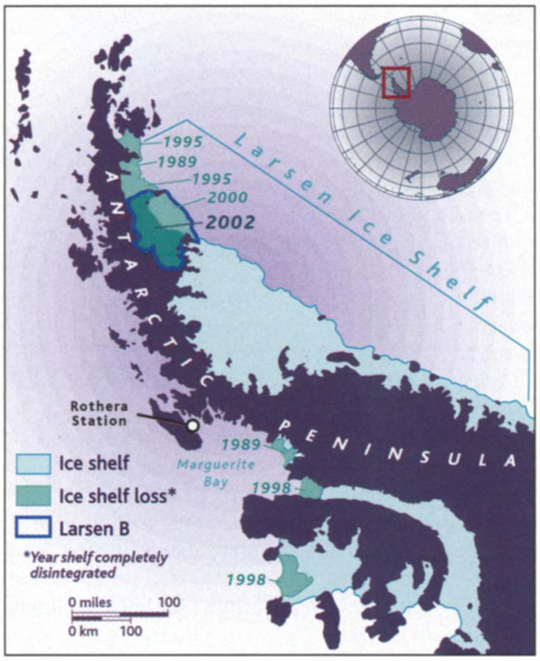
But the events unfolding on the peninsula could be harbingers of what might happen if the greenhouse effect heats up mainland Antarctica. The peninsula's ice shelves are miniature versions of two giant ice shelves that fringe the massive West Antarctic Ice Sheet. Fresh evidence from the peninsula is reviving concerns that loss of the floating shelves could hasten the demise of the continent's vast ice sheets, with catastrophic effects on global sea levels. Says glaciologist Richard Alley of Pennsylvania State University, University Park: "It makes me nervous about what's happening with those ice sheets."

Heat wave

After the gales died down and the clouds lifted on a 0°C February evening, mountain-rimmed Rothera Station could almost pass for an alpine ski resort. A couple of snowboarders, personnel of this BAS outpost midway along the peninsula's west coast, work their way down the southern tip of the Wormald Ice Piedmont glacier, sometimes skidding and losing their edge on ice below the thin snow. The makeshift ski slope has been ablating more and more every year since at least 1989, according to BAS measurements; most snow cover is gone by late summer. "These days, at the end of the season, it's only for expert skiers," says BAS meteorologist John King. More important, this end of the Wormald Ice Piedmont is receding, losing about 30 centimeters from its surface each year.

The thinning glacier is one of many disturbing signs of warming on the western Antarctic Peninsula, a strip of land dominated by a 1280-kilometer-long ice-capped mountain chain, the continuation of the Andes. Records from Rothera and six other weather stations going back to the 1930s clearly show a warming trend of about 2.5°C over the past 50 years. A similar, although smaller, trend can be inferred from oxygen-18 trapped in two ice cores from the top of the peninsula dating back several hundred years. Scientists blame this warming for ecological changes, including lusher, more abundant growth of the continent's two flowering plant species and fluctuations in penguin populations (see Croxall Review on p. 1510).

Yet the peninsula's fragile ecosystem has proven far more resilient than the ice has. Since 1950, 13,500 square kilometers of ice shelves—more than enough to cover Jamaica—have disintegrated. The retreat didn't attract widespread attention until 1978, when glaciologist John Mercer predicted in *Nature* that if global warming were to occur in Antarctica, the peninsula's ice shelves would be the first to succumb, melting before any of the continental ice did. By comparing air temperatures above existing and missing shelves, Mercer predicted that mean annual temperatures greater than –5°C would render a shelf vulnerable to collapse. With temperatures continuing to rise, says BAS glaciologist David Vaughan, the rest of the Larsen B ice shelf—another 3400 square kilometers—will probably be lost within a decade.



Falling like dominoes. The Antarctic Peninsula has lost large chunks of its ice shelves to climate warming in recent years.

Environmentalists have trumpeted the vanishing Larsen shelf as proof that human-induced warming is hammering Antarctica. Some scientists, however, argue that the peninsula's ice shelves might be in the warm phase of a natural cycle of melting and freezing. "If it happened in the past and the world didn't fall apart, maybe the sky's not falling now," says geologist Robert Gilbert of Queen's University in Kingston, Ontario. The frigid muck off the peninsula's coasts should provide some insight into whether such warming trends have, indeed, occurred before.

A muddied picture

The history written in the mud cores is reassuring—up to a point. Researchers who gathered at a workshop last April at Hamilton College in Clinton, New York, reported that at least some of the peninsula's dramatic warming has a precedent in the recent geological past.*

Parts of the peninsula, it turns out, experienced warmer periods earlier in the Holocene Epoch, the 11,000 years since the last ice age ended. At the meeting, paleontologists described the prevalence of diatoms—algae that leave behind tiny silica shells—as well as indirect indicators of marine life, such as organic carbon levels, off the peninsula's west coast. Their findings point to periods of more robust ocean productivity and, most likely, less sea ice between 9000 and 2500 years ago. For example, a group led by Amy Leventer of Colgate University in Hamilton, New York, found a diatom species called *Eucampia antarctica* in 6700- to 9000-year-old mud from Palmer Deep, near the peninsula's tip; currently the critter is usually found only in warmer waters farther north.

A toastier Antarctic scenario has also emerged from cores taken from the ice-packed Weddell Sea, off the peninsula's east coast. The Larsen Ice Shelf covered most of the peninsula's eastern flank for ages, until the collapse of its northern sections offered access to waters never before navigated.

One of the first scientific teams to venture into these virgin waters was a BAS crew led by Pudsey. That group sailed into Prince Gustav Channel at the peninsula's northern tip in February 2000, 5 years after a small ice shelf there had disintegrated. Sediment cores indicated that the shelf was absent as recently as 2000 years ago. As Pudsey's team reported in the journal *Geology* in September 2001, slate and granite pebbles in the sediment were completely different from rock from nearby sandstone and basalt islands. The slate and granite must have been carried there from afar by icebergs, Pudsey says, so "there must have been open water." In January 2001 in *Eos*, Hamilton College sedimentologist Eugene Domack drew a similar conclusion—open water 6000 to 2000 years ago during the mid-Holocene—from diatom layers in cores beneath Larsen A, the shelf's northernmost section.

* academics.hamilton.edu/workshops/antarctica

However, brand-new data from sediments that until recently lay beneath the Larsen B ice shelf tell a different story. Last winter, Domack's team, working on the U.S. National Science Foundation's *Nathaniel B. Palmer*, collected cores in waters where a section of Larsen B broke off in 1999. They found none of the diatoms unearthed beneath the ice shelves farther north. Based on the age of glacial till under Larsen A, Domack says, the erstwhile Larsen B was at least 11,000 years old, implying that the breakup is now extending farther south than ever before in the Holocene. If dating confirms the result, he says, it will mean that current warming on the peninsula's east side far exceeds any of the previous Holocene hot spells. And that, argues Princeton University atmospheric scientist Michael Oppenheimer, "shifts the balance of evidence in the direction of global warming being important" in the peninsula's climbing temperatures.

By air or by sea?

Even if the peninsula's current heat wave has no precedent in the Holocene, many scientists are not prepared to lay the blame solely on global warming. Some combination of three mechanisms might be going on, posits BAS's King: changes in atmospheric circulation, changes in ocean currents, and global warming. "If it were anthropogenic warming, it can't be anthropogenic warming on its own. There has to be something else," says BAS's Vaughan, whose group reviewed the possibilities last year (*Science*, 7 September 2001, p. 1777).

One idea is that there has been a shift toward warmer westerlies, the winds that sweep the peninsula's west coast. This concept gained support recently with a study that seemed to explain, for the first time, how Antarctica could be warming in some places and cooling in others (*Science*, 3 May, pp. 825 and 895). Those findings attributed the temperature tango to changes in the Antarctic Oscillation, a ring of high pressure that normally wanders but has recently tended to stay put, possibly because of ozone depletion. A similar phenomenon, the Arctic Oscillation, influences climate patterns in the far north (see p. 1491). But the Antarctic Oscillation study claimed only to explain half of the peninsula's warming.

Another possible factor is changes in ocean circulation that are driving deep, warm water toward the surface near the peninsula's west coast. That could be reducing the extent of winter sea ice, which in turn would warm the air because there would be less ice to reflect the sun's heat. Scientists have lacked a good long-term ocean temperature record that could verify this. However, two recent studies suggest that mid-depth waters in the Southern Ocean have warmed slightly since the 1950s (*Science*, 15 February, p. 1275; 19 July, p. 386). And new data presented at the Hamilton workshop suggest that in the past century, a diatom called *Thallossisia antarctica* found off the peninsula has begun assuming a warm-water morphology: The critters' silica shells are larger and now have spiky protrusions. "There is strong evidence for waters warming over the past couple of decades," Colgate's Leventer says.

Then there's the question of human-induced global warming. King and some fellow BAS scientists think that even a minuscule rise in air temperature could knock sea ice for a loop, ramping up temperatures much higher through a feedback effect. The main strike against this idea is that global climate models don't predict warming on the peninsula; the warming, these models augur, should be hundreds of kilometers to the west in the Bellingshausen Sea. Still, says King, the coarse models may fail to adequately represent the peninsula's knife-edge climate.

End of an era? Chunks of ice drifting from the disintegrating Larsen B ice shelf earlier this year. The shelf, seen here from the deck of the *James Clark Ross*, may have been intact for 11,000 years.

CREDIT: KEITH NICHOLLS/BRITISH ANTARCTIC SURVEY

Meltdown preview?

Although global warming could be a culprit in the peninsula's warming trend, there's no reason to panic over the loss of ice shelves: Because these displace their own weight, they don't raise global ocean levels when they melt. And it's unknown whether the peninsula's warming will propagate to mainland shelves, which lie in a different climate regime.

But the collapse of Larsen B and other peninsula shelves "could be a precursor to what's going to happen to the other ice shelves," says NASA glaciologist Eric Rignot. Under a widely accepted greenhouse-warming scenario, the mainland ice shelves would melt as sea temperatures rise. Because there would be less sea ice to block ocean water from evaporating and warmer air holds more moisture, much more snow would fall and the West Antarctic Ice Sheet would actually *gain* mass for 100 years. Then the rate of melting would begin to outstrip the rate of snow accumulation and the sheet would drain away some centuries later. The peninsula's ice shelves give scientists a chance to test this chain of events. That makes the peninsula "a natural laboratory," says Penn State's Alley.

Larsen B's death throes have already provided one eye-opener: They suggest that shelves can break up much faster than anyone thought. Colorado's Scambos is looking into exactly what happened before Larsen B's demise. He thinks that pools of meltwater on its surface spurred the breakup when the water's weight enlarged small cracks and forced them to propagate, leading to rapid shattering.

Scambos's team is now using Larsen B as "a road map" for modeling how ice shelves collapse. This is well worth doing, says Alley, who notes that although the continent's large shelves are nowhere near Mercer's magical melting number of an annual mean of –5°C, it wouldn't have to get that warm for melt pools to form in summer. "If meltwater is key," Alley says, "they may not be as far from [collapse] as we believed."

The demise of the peninsula's shelves could also sway a debate about the extent to which ice shelves buttress the sheets behind them. A few years ago, Vaughan and Chris Doake of BAS found that glaciers that fed the Wordie Ice Shelf on the peninsula's west side had not moved any faster since the shelf broke up in 1989. But the latest observations of the Larsen's remnants have found the opposite. Satellite observations show that glaciers behind Larsen A are moving up to three times faster now that the ice shelf is gone, a team led by Helmut Rott of the University of Innsbruck, Austria, reports this summer in the *Annals of Glaciology,* volume 34. "The acceleration is staggering," says Rignot, adding, "this paper came out of the blue."

The bottom line is that the Ross and Ronne ice shelves and their corresponding ice sheets could be more vulnerable than had been presumed. That comes on the heels of other unsettling evidence from Rignot's team that ice shelves are keenly sensitive to warmer ocean temperatures (*Science*, 14 June, p. 2020). "The most important information is that these glaciers can change tremendously rapidly," says Rignot, who now doubts the validity of the scenario in which mainland ice sheets gain mass before melting.

But many questions remain, and there are undoubtedly more lessons to be learned from the experiment in warming under way on the Antarctic Peninsula. That will keep scientists braving wicked weather to unearth the telltale warnings buried in mud and ice.

–JOCELYN KAISER