ICEBREAKER
Nathaniel B. Palmer takes scientists across the Weddell Sea near the coast of the Antarctic Peninsula.
As glaciers collapse toward the sea, scientists struggle to figure out how fast the southern continent is melting and what that means for sea-level rise

By Douglas Fox
Photographs by Maria Stenzel
IN 1995, 10 ARGENTINE SOLDIERS WITNESSED A CATACLYSM THAT NO OTHER HUMANS HAVE EVER SEEN, ONE THAT HAS SINCE ALTERED OUR UNDERSTANDING OF CLIMATE CHANGE.

The men were stationed at Matienzo Base, a dreary cluster of steel huts that sat atop a wedge of volcanic rock jutting from the sea, 50 kilometers off the coast of Antarctica. The island was surrounded by a plain of glacial ice covering 1,500 square kilometers—25 times the area of Manhattan. Although the ice shelf floated on the sea, it was 200 meters thick—as solid as bedrock. Yet Captain Juan Pedro Brückner sensed that something was wrong. Meltwater had formed ponds that dotted the ice. He could hear a gurgling sound as the water seeped down into a network of descending cracks. Day and night, Brückner's men heard deep convulsions that sounded like subway trains passing underneath their beds. The rumbles grew more and more frequent.

Then one day, while the crew ate lunch inside one of the huts, they were blasted by a boom—“calamitously loud, like a volcano blowing up,” Brückner recalls. They ran outside. The ice shelf bordering their little island was breaking apart. The upheaval was so violent they feared the fracturing ice would tear the island from its foundation and roll it like a log into the ocean. They placed instruments by their feet to warn them if the ground started to tip. After a few tense days the men were evacuated by helicopter to another station 200 kilometers north. The island held, but the map had changed for good.

Brückner and his colleagues had witnessed the collapse of the Larsen A ice shelf, a signature event. All told, as warm summers have reached farther down from the bottom of South America into the northernmost section of the Antarctic Peninsula, four ice shelves on the eastern side of the peninsula, including Larsen A, have collapsed in a striking pattern from the northern tip southward toward the Antarctic mainland.

Once a shelf disappears, towering glaciers that had piled up behind it in fjords along the sea’s edge are free to slide into the ocean. And slide they do, adding substantial volume to the sea. Scientists still do not know what triggers the breakup of an ice shelf or when future ones will occur, so they struggle to estimate how quickly glaciers will dump their ice into the ocean and therefore how much sea level will rise. Although the landmark 2007 report by the Intergovernmental Panel on Climate Change (IPCC) estimated that sea level will rise by just 18 to 59 centimeters by 2100, glaciologists worry that increasingly quick climate change could accelerate glacier melt 10-fold, thus pushing sea level much higher than anticipated. The ice shelf breakups might just provide that feedback.

The Antarctic Peninsula holds only a small fraction of the continent’s ice, but it is “a natural laboratory,” says Theodore Scambos, a glaciologist at the National Snow and Ice Data Center in Boulder, Colo. “It’s the trailer for the movie that’s going to unfold over the rest of Antarctica for the next 50 to 100 years.”

Understanding this natural experiment has become an urgent priority. Scientists need to know how fast the ice shelves are disintegrating and what is causing the demise so that they can better estimate future sea-level rise. “Time and again, the models are conservative, and they’re underestimating the mag-

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**IN BRIEF**

Massive ice shelves that cling to the edges of Antarctica are breaking apart, and their collapse is allowing enormous glaciers behind them to slide into the ocean, raising sea level. Scientists need to better understand why and how fast the ice shelves are disintegrating so that they can better estimate future sea-level rise. Satellite data about glaciers are not detailed enough for accurate estimates. Scientists have made recent expeditions to Antarctica to install instruments that will give them the information they need. Author Douglas Fox accompanied them on an eventful eight-week trip and documents that experience here. He also describes the data now streaming in and what they predict for the planet.
Less Ice, More Snow

Change is rapid along the Antarctic Peninsula (below), where annual air temperatures are rising and glaciers are accelerating toward the sea (bottom). Inland elevation is up in spots because of more snowfall (below, right), but Antarctica still loses up to 190 billion metric tons of ice a year.

Temperatures Rise

Massive ice shelves have been crumbling in a pattern from north to south, as a mean annual temperature line of ~9 degrees Celsius advances in that direction. Scientists predict the Scar Inlet ice shelf will disappear next.

Elevations Change

As glaciers melt, their elevations decrease. Yet some inland regions are rising; warmer temperatures increase ocean evaporation, bringing more snow to the interior and raising the ice pack. Still, glacier loss is far greater than snow gain.

Glaciers Flow

Once an ice shelf collapses, glaciers on land behind it accelerate toward the sea [see box on next page]. Although the glaciers surge and slow, their average flow speeds have increased significantly.

Increase in Glacier Flow Speed (between 1999 and 2008)

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*Between 1995 and 1999  †Among 2001 and 2009
nitude of change,” says Robert DeConto, an ice sheet modeler at the University of Massachusetts Amherst. “We’re sitting on our hands waiting for data.” Researchers on recent expeditions to the frozen continent have planted instruments that are giving scientists the information they need, and the latest projections from those data are alarming.

**A HARD BOUNCE OFF ICEBERG UK211**

The first documented disappearance of an Antarctic ice shelf occurred around 25 years ago. The Larsen Inlet ice shelf, a 350-square-kilometer slab north of Larsen A, was present in a satellite photograph taken in 1986, but by the time another image was made in 1988, most of it was missing. No one had any sense of how it might have vanished.

The austral summer of 1995 opened some eyes. Just as Larsen A underwent its now notorious collapse, the Prince Gustav ice shelf, 60 kilometers to the north, also vanished. “The disintegration came as a total surprise,” says Scambos, who, with scientists at the British Antarctic Survey, has been monitoring the continent’s ice shelves continually via satellite for many years. The effects of these breakups have reverberated throughout the region. In aerial photographs taken before Prince Gustav disappeared, Sjögren Glacier was a smooth-surfaced plume that sloped gradually from the mainland far out into the fjord, inching toward the ice shelf and sea. But 15 years later Sjögren is a sorry sight, wrinkled with crevasses and sagging in the middle. After the Prince Gustav ice shelf disappeared, Sjögren accelerated toward the ocean at several times its former speed. Crevasses 20 meters wide opened across its surface as the 600-meter-thick ice below stretched under the seaward deformation. Enormous icebergs splintered, uncontrolled, off Sjögren’s front edge; that edge now sits 15 kilometers farther back into the fjord than it used to.

“Every single glacier that flowed into an ice shelf, when the shelf was removed, suddenly accelerated,” Scambos says. “Not just a little bit but by a factor of two, three, five, up to eight times as fast.”

Seven summers later, in 2002, the Larsen B ice shelf, just south of Larsen A and 55 times larger than Manhattan, disintegrated into hundreds of shards the size of skyscrapers. “We could see whales in places where the ice was 300 meters thick a few days earlier,” says Pedro Skvarca, a glaciologist with the Argentine Antarctic Institute in Buenos Aires who flew over the site in a plane shortly afterward. “We were quite astonished.”

Once again, the demise of floating ice removed the backstop...
UK211 was a free-drifting berg, not an ice shelf, Scambos could only describe the moment of disintegration—only what led up to it. And because the berg was softening and bending, water may have percolated into the berg’s interior and destabilized it. The melt that followed the berg’s surface into waterlogged slush. The meltwater may have percolated into the berg’s interior and destabilized it, Scambos says. But the experiment did not show him the moment of disintegration—only what led up to it. And because UK211 was a free-drifting berg, not an ice shelf, Scambos could not quantify how glaciers feeding into the berg would respond.

The berg, shaped like the long, narrow geometric blocks that descend in the game Tetris, rolled off the edge of the ice shelf and into the ocean to reveal their cross sections of blue glacial ice. Researchers had never seen this pattern of calving before. The ice shelves were dying from some heretofore unrecognized mechanism.

Scambos and Skvarca first attempted to understand that mechanism of collapse in March 2006. On a dim, cold day an Argentine naval helicopter landed on a broad, tabular berg with a precarious, sideways bounce; the pilot, thrown off by the berg’s uniform milky white color, did not realize that his spinning rotors had dipped dangerously low. Scambos, Skvarca and four other scientists climbed out of the helicopter. This iceberg, named UK211, had survived for three years since calving off the Larsen C ice shelf 385 kilometers south, but now it was drifting into warm climates north of the peninsula. Scambos and the others hoped to use it as an experimental analogue for ice shelf breakup.

The team installed an instrument station, dubbed AMIGOS (Automated Met-Ice Geophysics Observation Systems), that would monitor the berg’s deteriorating health. A GPS unit tracked the berg’s position, a meteorological station measured wind and temperature, and a camera documented snowmelt on the surface. The camera could be aimed at a marked pole driven into the berg to show how quickly the snow level dropped as the result of melting. The camera could also be aimed at a line of poles that the researchers planted 2.2 kilometers out toward the berg’s edge. If that line started to curve, it would indicate that the berg was softening and bending.

Scambos and Skvarca tracked UK211 for eight months, communicating with AMIGOS by satellite phone. The berg, originally 10 by 12 kilometers, slowly shrank by half. Then, on November 23, 2006, AMIGOS phoned home for the final time. A few days later UK211 was gone, sending AMIGOS to the bottom of the sea.

UK211 underwent many changes, but one that immediately preceded its sudden demise was the melting of snow that transformed the berg’s surface into waterlogged slush. The meltwater may have percolated into the berg’s interior and destabilized it, Scambos says. But the experiment did not show him the moment of disintegration—only what led up to it. And because UK211 was a free-drifting berg, not an ice shelf, Scambos could not quantify how glaciers feeding into the berg would respond.

TRAPPED GLACIOLOGISTS FIND A WAY

Those questions led Scambos to join a difficult but critical expedition in 2010 to a remnant of Larsen B called the Scar Inlet ice shelf. A laser altimeter onboard the ICESat satellite had documented the thinning of glaciers feeding into Larsen B and Scar Inlet—as indicated by lowering of the ice surface—but the altimeter had failed out earlier that year. Interferometric synthetic-aperture radar measurements from other satellites had provided long-term averages of how quickly glaciers behind ice shelves like Scar Inlet were flowing into the sea, but the technique would not capture sudden events like glacier surges. Since 2003 the GRACE satellites had measured ice loss through variations in the earth’s gravitation but only at the fuzzy resolution of hundreds of kilometers.

Scambos expected the Scar Inlet ice shelf to collapse within a few years, and he wanted to plant an array of sensors on the ground there to capture the cataclysm. “We want to watch this process from the very beginning and in greater detail than what we’ve seen from satellites,” he told me in 2010, as we sat indoors on the Nathaniel B. Palmer, a 6,000-metric-ton icebreaker that serves the U.S. Antarctic Program. “We want to see the big show at the end.”

For 57 days in January and February 2010, the Palmer plowed along the peninsula toward Scar Inlet, ramming through seasonal sea ice up to two meters thick. Scambos and two dozen scientists onboard had hoped to get close enough to fill in critical blind spots in their knowledge. They ran into trouble only days into the expedition, however. Severe sea ice, pushed up against the peninsula by ocean currents and winds, prevented the Palmer from getting within easy helicopter range of Scar Inlet. So, on January 26, Scambos was dropped off at a British research station with four other glaciologists, including Martin Truffer and Erin Pettit of the University of Alaska Fairbanks. From there a Twin Otter plane delivered them to their first field site. The team spent three weeks hopping by plane between the Scar Inlet ice shelf and the glaciers feeding into it.

On days when snowstorms subsided, the researchers installed AMIGOS on Scar Inlet and on the lower reaches of Flask Glacier (and they plan to install another AMIGOS on the lower Leppard Glacier in 2013). Higher up on Flask and Leppard, they installed simpler meteorological and GPS stations. On a coastal bluff overlooking Scar Inlet, they mounted a steerable camera.

Scambos’s team members encountered unexpected conditions on the Scar Inlet ice shelf. When they dug in and around camp, their shovels plunged into empty voids—crevasses in the ice veiled under thin crusts of snow. One day the plane’s pilot sunk up to his waist in another hidden crevasse. Those cracks may have previously been buried under thicker snow, but hot summers had melted it away, bringing the cracks to the surface—just as Brückner and his Argentine soldiers had seen in the last days of Larsen A.

One summer soon the Scar Inlet ice shelf will cross a critical threshold. Repeated cycles of melting and refreezing will harden its surface until it can hold large melt ponds. Those ponds will drain into exposed crevasses. As water accumulates in crevasses, its weight will drive the cracks deeper—“like a wedge,” Scambos

July 2012, ScientificAmerican.com 59

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says—until they reach the bottom of the ice, breaking off a long, skinny Tetris berg. The rupture of one crevasse will produce shock waves that will set off others closer to land’s edge. The entire ice shelf might disintegrate within only a few days—maybe just hours.

That is how Scambos thinks Scar Inlet will die. The AMIGOS will let him test the theory. Their cameras will show melt ponds forming, crevasses opening and ponds draining into them. Shots of the pole lines will show the ice shelf straining and buckling. The ridgetop camera will record the pattern of iceberg calving. The AMIGOS on Flask and Leppard will show how the glaciers speed up as the ice shelf holding them back collapses. By having upstream and downstream stations on each glacier, Scambos will see the dynamic nature of glacial response—the manner in which the bottom of the glacier accelerates before its higher reaches do, thus causing it to stretch, thin and welt up with crevasses the way Sjögren Glacier did. The Scar Inlet ice shelf, Scambos says, “is teetering on the edge.”

ROCK, DATA, SCISSORS

Glaciers on the Antarctic Peninsula that have lost their ice shelves are indeed thinning at a rapid rate of five to 10 meters a year. The data come from laser altimetry measurements that were taken by the now defunct ICESat and, more recently, by aircraft. The crucial question is how this rate compares with the gradual thinning that has happened since the close of the last ice age 12,000 years ago—and in particular, whether the recent ice shelf breakups are truly unprecedented. Greg Balco, a geologist at the Berkeley Geochronology Center who was on the Palmer, wanted to answer this question.

On a cold, overcast morning a helicopter ferried Balco and me from the Palmer to Sjögren Glacier, 30 kilometers west. Sjögren’s fjord held ice 600 meters thick as recently as 1995, right before the Prince Gustav ice shelf broke up, but now it holds seawater instead.

The helicopter dropped us on a bare, rounded mountain beside the fjord. The peak’s gray-and-white-layered bedrock was worn into smooth curves and was raked with scrape marks—scars that a younger, thicker Sjögren Glacier left as it rote over this terrain thousands of years ago. “This is beautifully polished,” Balco said of the bedrock. “It looks like it deglaciated last week.” Scattered all around were stones that did not match the bedrock—a brown volcanic boulder here, granite over there. Sjögren had carried them in from far away and dropped them in their present locations as its ice melted.

Balco used these oddball rocks to figure out how quickly Sjögren Glacier has thinned over thousands of years. He picked his way uphill, collecting rocks at different elevations. Back home, he analyzed them to see how long they had been exposed to sunlight by measuring tiny amounts of a rare isotope called beryllium 10, which forms when cosmic rays strike stone. By measuring how long rocks at different heights on the mountain have seen sunlight, Balco could calculate how quickly the glacier thinned and reexposed the mountain.

A year after the expedition Balco had analyzed rocks collected from around two glaciers—Sjögren and Drygalski. His results suggested that the glaciers have undergone major retreats at least once in the past 4,000 years—indicating that both the Prince Gustav and Larsen A ice shelves had collapsed at least once in that time.

Balco never reached Larsen B because of the ship’s problems with sea ice, but Eugene Domack, the marine geologist who led the 2010 expedition, has already estimated the age of the Larsen B ice shelf. Domack, an environmental studies professor at Hamilton College, managed to reach the Larsen B area during earlier cruises. His team bored several three-meter-long columns of sediment from parts of the seafloor that were covered by Larsen B until its collapse. Cores taken from under the open ocean are often stained green from microscopic plants called diatoms that settle to the seafloor after dying, but this core contained none. Layer on layer of fine, sandy mud created by grinding glaciers revealed that Larsen B had shaded this area for at least 11,000 years. Layers in the core were dated by analyzing the carbon 14 content of shells left by microscopic organisms called foraminifera.

Eleven thousand years is as far down as Domack’s core reached. He says, however, Larsen B may have persisted as far back as 100,000 years, the beginning of the last ice age. Taken together, Balco’s and Domack’s results suggest that the northernmost ice shelves on the Antarctic Peninsula have come and gone in the past. But as the chain of ice shelf collapse pushes farther south from the peninsula’s tip toward the mainland, to Larsen B and Scar Inlet, it is now entering the ominous realm of historical anomaly.

IMPLOSION, THEN ACCELERATION

Eighteen months after the Palmer returned to port in Punta Arenas, Chile, Scambos reviewed the data streaming in, via satellite, to his office in Boulder. The Scar Inlet ice shelf still has not collapsed—but instruments on the ground had already revealed other insights that were totally unexpected. Researchers had assumed, for example, that even if the peninsula’s ice shelves experienced brutal summers, the winters would still nourish them with new snow. Yet when Scambos and his team had returned in November 2010 to repair the station, they found the Scar Inlet ice shelf too crisscrossed with exposed crevasses for their plane to land. As the Twin Otter skidded overhead, the boot and skid marks that they had left nine months earlier were still visible: a winter that should have nourished Scar Inlet with new snow left it, instead, one step closer to collapse.

Another surprise had occurred that same year between July 14 and 15, during the dark depths of the polar winter. The AMIGOS on Scar Inlet reported a heat wave. The temperature suddenly shot up by 43 degrees Celsius, topping out at a toasty 10 degrees C—shirtsleeve weather in Boulder. The heat was driven by westerly “foehn” winds, which formed as air sliding down the mountains of the peninsula compressed and warmed. At the same time, thermistors buried several meters into the ice at the AMIGOS site recorded a pulse of warmth—suggesting that water from snowmelt was percolating down.

No one knows how often these foehn winds happen—but, Scambos says, “we could be missing some important facts.” The average speed of winds blowing off Antarctica’s coastlines has in-
creased by 10 to 15 percent over the past 30 years. Wind now scour 50 billion to 150 billion metric tons of snow from Antarctica’s surface each year, blowing it into the ocean, where it melts. As winds strengthen, scouring will likely increase, potentially worsening the prognosis for ice shelves in a way no one anticipated.

What is more, three precision GPS units that Domack had bolted into bedrock outcrops around the perimeters of Larsen B and Scar Inlet show that this region is now rising 1.8 centimeters a year. The disappearance of heavy glaciers is allowing the earth’s crust below to rebound—“remarkably fast,” Domack says, and far greater than the 0.8 centimeter estimated from a GPS station 150 kilometers away. The rate of tectonic uplift will increase again when the Scar Inlet ice shelf implodes and the glaciers behind it surge into the ocean. Measure that uplift, Domack says, and you can estimate the amount of ice spilling out. Do that at Scar Inlet, and you can better predict how much ice will disappear as other ice shelves succumb farther south.

That more ice shelves will collapse is a foregone conclusion. An average summer temperature of zero degrees C seems to represent the highest temperature at which an ice shelf can exist. And the invisible line where summer averages zero degrees C is creeping south along the Antarctic Peninsula tip toward the mainland, along with higher mean annual temperatures. Every ice shelf that the line crosses has collapsed within a decade or so. Next up, south of Larsen B and Scar Inlet, is the Larsen C ice shelf, which covers 49,000 square kilometers—twice as large as the state of Maryland, or about 820 Manhattans. Larsen C has more glacial ice flowing into it than all the other ice shelves that have collapsed combined. It already sees summer melt ponds on its northern end.

Even more worrying are the ice shelves hanging off the mainland, which support much larger glaciers, such as Pine Island, Thwaites and Totten. They are melting from their undersides because of warmer ocean currents, rather than from the top down. The result is the same: Pine Island Glacier has thinned by only 15 percent since 1994, yet the massive glacier behind it has accelerated by 70 percent.

The full effects of ice shelf breakup on glacier demise will not be known for some time. A study published in 2011 by Scambos, Truffer and Petit found that one glacier continues to accelerate even 15 years after losing its ice shelf: Röhss Glacier (which used to flow into the Prince Gustav ice shelf) has now reached nine times its former speed.

This acceleration in glacier flow may explain a recent observation by Eric Rignot and Isabella Velicogna of the NASA Jet Propulsion Laboratory. They found that the rate of ice loss from Antarctica is actually increasing by roughly 25 cubic kilometers a year. Those 2007 IPCC estimates of 18 to 59 centimeters of sea-level rise by 2100 do not account for any of these ice shelf effects. The estimates “actually send the wrong message,” Rignot says. “They’re probably off by a factor of two to three.” By 2100, he says, “you could easily see a meter of sea-level rise.” An analysis published in 2009 by Martin Vermeer of the Helsinki University of Technology places the estimate between 75 and 190 centimeters.

Such hints beg further monitoring of the Larsen region—an area that punishes those who try to pry apart its secrets. Prior to the 2010 Palmer expedition Domack had sailed to the area on five earlier research cruises, three of which never reached their geographic target because of brutal sea ice. “It can be really frustrating,” he admits. But important questions are bound to keep him and Scambos coming back.

MORE TO EXPLORE


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See photographs of scientists doing the glacier and ocean fieldwork described in this article at ScientificAmerican.com/jul2012/antartica

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