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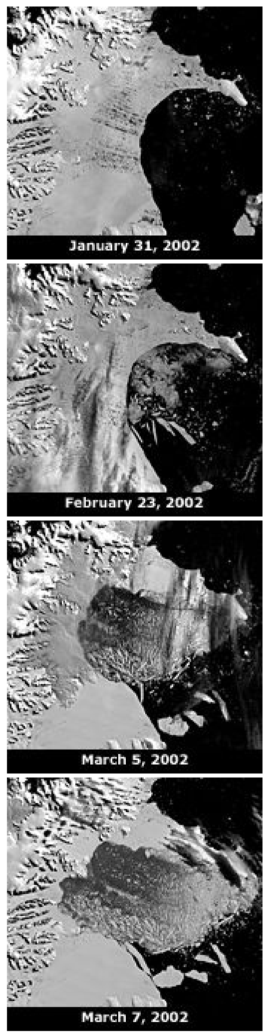
Title graphic: The Larsen B Ice Shelf had shattered by the time this photo was taken on March 8, 2002. (Image courtesy of Keith Nicholls, British Antarctic Survey)

For hundreds of thousands of years, ice shelves along the Antarctic coast retreated and advanced unobserved by the human eye. In March 2002, however, a group of scientists had a front row seat for the largest ice shelf breakup in recent history.

An ice shelf is a floating platform of ice, usually fed by mountain glaciers or ice sheets. Typically, ice shelves advance over the ocean for several decades until they become unstable, at which point large icebergs break off, or *calve,* from the ice shelf front. Advancing and retreating in this manner is a normal process for maintaining mass balance, or ice volume. However, the splintering and shattering observed in some ice shelves is unprecedented in recent history.

The Larsen Ice Shelf complex stretches along the eastern edge of the Antarctic Peninsula — a finger of land pointing crookedly toward the tip of the South American continent. Scientists have divided the shelf into three sections: the Larsen A, B, and C Ice Shelves. The Larsen A and B shelves existed near the northern tip of the peninsula. The Larsen C Ice Shelf flows from the central portion of the peninsula and represents the southern section of the Larsen shelf complex.

Scientists had been observing the Larsen B for several years, assuming that it would eventually retreat. But they were stunned to see the ice shelf disintegrate in a mere 35 days. Between January 31 and March 7, 2002, the ice shelf lost 3,250 square kilometers (about 1,255 square miles) — an area somewhat larger than Rhode Island — sending a plume of icebergs into the Weddell Sea.




MODIS captured the disintegration of the Larsen B between January 31 and March 7, 2002. (Images courtesy of Ted Scambos, National Snow and Ice Data Center.)

The disintegration of the Larsen B Ice Shelf followed several other ice shelf retreats over the past two decades. Scientists have come up with a number of theories to explain why these dramatic breakups are occurring. Some believe that various forces may compromise the internal strength of the ice shelves. Others profess that a decrease in sea ice coverage has left shelves vulnerable to ocean swells. Although many of the questions about ice shelf disintegration remain unanswered, satellite imagery is providing at least one perspective.

The recent Larsen B disintegration supports a theory developed by Ted Scambos, research scientist at the National Snow and Ice Data Center in Boulder, Colorado, and his colleagues, Christina Hulbe, associate professor at Portland State University, and Mark Fahnestock, assistant research scientist at the University of Maryland. The researchers theorized that melt water collecting on the ice shelf surface during unseasonably warm summers might be a primary mechanism in ice shelf breakup.

Most ice shelves exhibit some surface melting each summer, but the melting is usually not widespread enough to affect the structural integrity of the ice. However, if summer temperatures are warm enough, significant amounts of melt water can accumulate on ice shelf surfaces, often forming ponds and even streams. Scambos and Hulbe suspected that excess melt water affected the structural integrity of the ice shelf, particularly in heavily fractured areas. “Melt ponds give us a mechanism that makes a nice connection between atmospheric warming and ice shelf disintegration,” said Scambos.

Scambos, Hulbe, and Fahnestock examined each new breakup event, searching for features that would account for dramatic changes in calving style among peninsular ice shelves. In 1993, Scambos began monitoring the Antarctic Peninsula using satellite imagery from the Advanced Very High Resolution Radiometer (AVHRR) sensor. AVHRR-derived images allowed him to monitor flow features, surface melt water, crevasses, and cracks developing in the ice. “The AVHRR data set enabled us to build up a pretty good record of the Antarctic coastline, and we could then start speculating about the formation of melt ponds and where the breakups were occurring,” said Scambos.

In 2001, Scambos began using NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to monitor the Antarctic Peninsula with even greater detail. The MODIS sensor is more sensitive to slight variations in reflected light, making it ideal for imaging ice surfaces. “We can see tinier cracks, smaller hills and bumps, and fainter flow features of the ice sheet, which reveals a lot about the flow history of the ice shelf and about whether a specific area is experiencing melting,” said Scambos.

While Scambos monitored the shelves using satellite imagery, Hulbe used a variety of data to model the effect of melt water on surface crevasses in ice shelves. Her results showed that melt water, which collects naturally in crevasses, could force even relatively shallow cracks to propagate, or push through, the full thickness of an ice shelf if water continually occupies at least 90 percent of the crevasse. “When a fracture cracks, it relieves the stress that caused it to crack in the first place. But the tip of that crack becomes a focus at which new stress accumulates, and when the stresses again become large enough to overcome the strength of the ice, the fracture cracks again,” said Hulbe. In the case of the Larsen B, excessive melt water was providing the constant stress needed to push fractures through the ice shelf, which was 220 meters (about 720 feet) thick in places.

The pressure exerted by the melt water is greater than that of the ice, especially if the crevasses are filled with water throughout most of the melt season, as they were on the Larsen B during the 2002 summer season. “If this process continues for something on the order of a decade, the ice shelf will probably disintegrate. That’s been the track record for the Larsen,” said Scambos.

MODIS images of the Larsen B Ice Shelf, dating from January 31 through March 7, 2002, demonstrate the melt water fracturing theory. The first image, taken on January 31, shows extensive melt ponds. Subsequent images taken on February 17 and 23 reveal that the melt ponds disappeared, indicating that the melt water may have drained through the crevasses. Finally, a March 7 image shows that most of the ice shelf had disintegrated. The shattered areas exactly matched the locations that had been covered by melt ponds only a few weeks earlier.

Although the 2002 Larsen B disintegration supports the melt water fracturing theory, David Vaughan, a glaciologist at the British Antarctic Survey in Cambridge, England, suggests that other mechanisms

### Ice Shelves and Sea Level Rise

The disintegration of the Larsen B Ice Shelf will not affect sea level any more than a melting ice cube would raise the level of water in a glass of ice water. However, even though disintegrating ice shelves do not contribute directly to sea level rise, they might do so indirectly. Acting more or less as a brake, ice shelves hold back the glaciers or ice sheets feeding the ice shelves. For instance, scientists have detected increased flow speeds in glaciers that previously fed the Larsen A Ice Shelf. These glaciers now feed directly into the Weddell Sea, which leads to more icebergs being discharged into the ocean. While the amount of ice in these icebergs is itself inconsequential, the Larsen A provides a model for what may happen if a larger ice shelf like the Ross Ice Shelf were to collapse. Without the Ross Ice Shelf acting as a brake, the West Antarctic Ice Sheet could disgorge an amount of ice equivalent to about five meters (about 16 feet) of sea level rise.

For more information, visit Antarctic Ice Shelves at the National Snow and Ice Data Center DAAC.

might prove to be equally instrumental in ice shelf breakup.

"As the ice shelf warms up, the actual strength of the ice may change. Free water between the ice crystals could lubricate and promote fracture growth," said Vaughan. "And when temperatures are warmer, there's less sea ice protecting the ice shelf from the ocean swell." Vaughan cites several other possibilities, including possible changes in atmospheric and ocean circulation in the Antarctic region.

Unlike the melt water fracturing theory, which is easy to monitor using satellite images, other theories require *in situ* measurements that can be difficult to obtain. A crewmember of the British Antarctic Survey research vessel, *James Clark Ross,* photographed the aftermath of the Larsen B breakup. But according to Vaughan, it was pure luck that the ship happened to be in the area. "Most ship research schedules are determined years in advance, making it virtually impossible for researchers to obtain a ship on short notice. In addition, not all ships have helicopter facilities, meaning researchers can't be flown ashore," he said.

Cracks lined the remaining Larsen B Ice Shelf south of the Seal Nunataks on March 13, 2002. (Image courtesy of Pedro Skvarca, Instituto Antártico Argentino)

"I don't think we can look at these other processes using satellite data. If we're actually trying to see how the material properties of ice shelves change as the temperatures increase, then we actually have to go there," said Vaughan. Vaughan, Hulbe, and Scambos all cite the work of Pedro Skvarca, head of the Glaciological Division of the Instituto Antártico Argentino in Buenos Aires, who had been conducting field studies on the Larsen B Ice Shelf. "Now that the shelf is gone, the data that Skvarca collected over the last 10 or 15 years is treasure," said Vaughan. Skvarca and his team were the last people to set foot on the northern part of the Larsen Ice Shelf.

Scambos and Hulbe plan to continue monitoring Antarctic ice shelves and surface melt ponds using MODIS and AVHRR. Vaughan plans to keep an eye on the Wilkins and Larsen C Ice Shelves, both of which may retreat if warm temperatures persist. He also hopes to investigate more thoroughly how ice shelves and dense, salty Antarctic bottom water affect ocean circulation.

While hesitant to blame the disintegration on global warming, many researchers agree that summer temperatures play a role in the unusual warming trend along the Antarctic Peninsula. "Climate seems to have been relatively stable on the Antarctic Peninsula for the past 1,800 years, but then 50 or 100 years ago, it began to change," said Vaughan.

Indeed, weather records over the past 50 years show that regional air temperature increased 2.5 degrees Celsius (4.5 degrees Fahrenheit) — five times the rate of warming measured for the rest of the world. And records from Orcadas Station (located in the South Orkney Islands, northeast of the peninsula) indicate that regional warming along the peninsula occurred as early as the 1930s. “That’s fairly strong evidence to suggest that this is not part of natural variability,” said Vaughan.

The disintegration of the Larsen B may simply be evidence of how quickly certain regions of the world can respond to relatively small climate changes. The regional warming observed in the Antarctic Peninsula represents a small part of a much larger picture, and scientists hope to gain a better understanding of the complex interactions between ice, oceans, and atmosphere.

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