

How much of the Earth's ice is melting? New and old techniques combine to paint a sobering picture

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As climate change warms our planet, the world's ice is melting faster than ever. Glaciers are retreating in most mountainous regions. The ice sheets that cover Greenland and Antarctica are thinning. The dramatic loss of land-bound ice is already raising sea levels, posing a growing threat to billions of people who live in coastal areas.

Meanwhile, the floating ice that drifts atop the Arctic Ocean is disappearing, and the ice shelves that fringe Antarctica and Greenland are breaking up. Ice shelves can act as buttresses that slow the flow of glaciers into the sea—without them, onshore ice reaches the ocean more quickly, causing even greater sea-level rise.

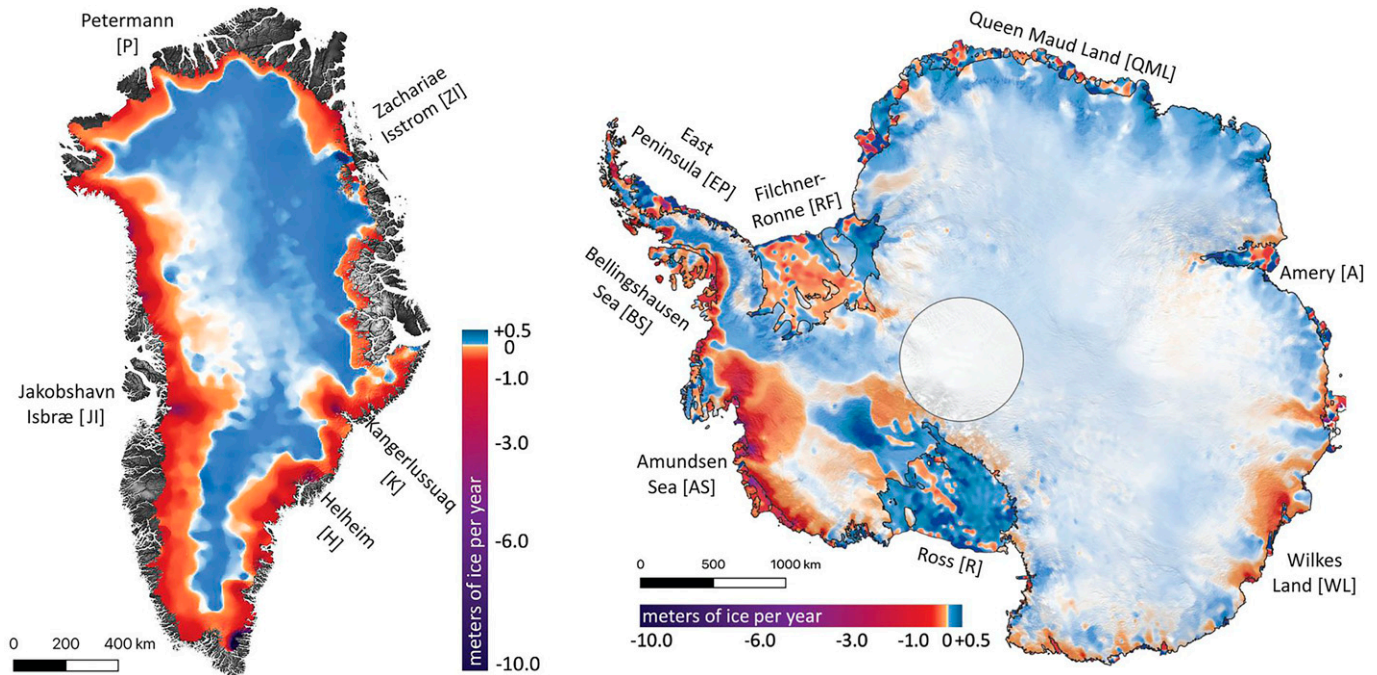
For many years, researchers relied solely on fieldwork to study ice melting. It's still a vital component. But over the past few decades, researchers have been joined by a burgeoning fleet of instruments on aircraft and satellites that gather a broader swath of data from on high.

Together, the latest findings are providing a much clearer, more comprehensive picture of Earth's ice loss—and that picture looks increasingly dire. "We're seeing melting in places that haven't melted before," says Benjamin Smith, a glaciologist at the University of Washington in Seattle. This constellation of observing platforms is also showing precisely how much ice is melting at key locations and starting to explain why those places are particularly vulnerable to global warming. Data gathered in the past few years are now honing researchers' predictions of how much sea levels will rise in decades to come.

The base of ice sheets can warm as a result of moulins, formed when large amounts of precipitation and surface meltwater pour down through a natural hole in the ice. Image credit: Poul Christoffersen.

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Between 2003 and 2019, some regions of Greenland (Left) and Antarctica (Right) lost several of meters of ice per year. Image credit: Reprinted with permission from Ref 1.

From Above and Below

Satellites have been monitoring Earth's ice since the late 1970s. Aircraft-mounted instruments and GPS-laden sleds towed by snowmobiles have provided a way to check those space-based measurements at many sites worldwide; they still help to ground-truth satellite accuracy.

Researchers have used satellite observations of ice thickness, ice velocity, and climate models to estimate how much ice has disappeared from Earth's ice sheets in recent decades. Other teams have used the relative motions of pairs of satellites to more directly measure ice loss on a broad scale. But now NASA's ICESat-2, a satellite launched in 2018, is measuring ice loss at a large number of closely spaced, very small spots. Its sole instrument is a laser altimeter that calculates the elevation of Earth's surface by measuring how long it takes for a laser pulse to travel from the satellite to the ground and back again. These readings can reveal changes in the thickness of ice on the ground with an astonishing accuracy of about 2 millimeters, says Smith. From these changes in ice elevation, researchers can estimate the mass of ice being lost or gained at each spot. Summing up those estimates enables the researchers to assess ice losses or gains over broader areas.

Day by day, ICESat-2's near-polar orbit gradually shifts so that it can gather elevation data at sites worldwide, except for areas less than 450 kilometers from the North and South Poles that the probe never sees. The probe fires its laser every 170 meters along its path and returns to the same ground track every 91 days. By taking readings from each point on the ground four times per year, the probe can pick up any variations in elevation from season to season, and from year to year, revealing changes in the amount of ice in Earth's high-latitude regions and in its glaciers. "We're quite staggered by the amount of data we're getting," says oceanographer Helen Fricker at the Scripps

Institution of Oceanography in La Jolla, CA, alluding in part to how ICESat-2 compares with its predecessor.

To estimate recent ice loss, a team including Fricker and Smith compared data gathered by ICESat-2 in 2018 and 2019 with data collected by the original ICESat from 2003 to 2009 (1). The researchers found that the ice had thinned considerably around Greenland's edges, where ocean currents flow beneath floating ice masses and melt them from below. At locales near Greenland's two largest outlet glaciers, the floating ice masses had thinned by 4 to 6 meters per year. In comparison, at the highest elevations of Greenland's ice sheet, snow accumulation led to an elevation boost of fewer than 15 centimeters per year. Overall, the Greenland ice sheet lost a whopping 200 billion metric tons of ice per year between 2003 and 2019, the researchers estimate, releasing enough water to fill 80 million Olympic-sized swimming pools.

In Antarctica, which is much colder than Greenland, the estimated ice losses are lower but still substantial. Whereas ice shelves fringing the continent increased their mass by about 15 billion metric tons per year, largely owing to growth in their area rather than their thickness, the onshore portions of the Antarctic ice sheet lost around 118 billion metric tons of ice per year during the study period.

The overall pattern in both Greenland and Antarctica is that inland snow accumulation wasn't nearly enough to make up for increased ice melting in many other locales. Together, Antarctica and Greenland lost enough ice to boost sea level by about 14 millimeters between 2003 and 2019, Fricker and her colleagues say. "ICESat-2 gives us a more concrete, big picture view than we've ever had before," says Smith.

The new ICESat-2 findings are largely in line with data gathered by satellites in the Gravity Recovery and Climate Experiment (GRACE) mission, a joint effort of NASA and the German Aerospace Center that collected data from March



Unmanned aerial vehicles (UAVs) are among the tools that researchers use to monitor drainage from the meltwater lakes that sit atop ice sheets. Image credit: Tom Chudley.

2002 to October 2017, and its follow-on mission that launched in May 2018. Those data show that between 2002 and 2020, Antarctica shed about 150 billion metric tons of ice per year, whereas Greenland lost about 280 billion.

All About the Base

Greenland's land-bound ice sheet isn't only melting on the surface and around its edges. It's also melting from below in some spots—and at surprisingly high rates, researchers say.

Poul Christoffersen, a glaciologist at the University of Cambridge, UK, and his colleagues have been studying a site atop Store Glacier since 2014. There, 30 kilometers inland from the western edge of Greenland's ice sheet, the ice is a little more than 600 meters thick. The researchers have been assessing ice melt at the surface and gathering temperature and pressure data from sensors installed at the base of the ice. They also use ground-based ice-penetrating radar to monitor the thickness of the ice and of the water layer between the base of the ice and the underlying bedrock. By gathering data from atop the ice, the researchers can get a more accurate picture of ice melt than from space- or airplane-based instruments.

In their latest study, published in February, the team looked at radar data collected once every 4 hours from early August to early December 2014. The team's analysis revealed that the average melt rate at the base of the ice sheet for that period was about 14 millimeters per day (2). As might be expected, the melt rate was somewhat higher during the summer months. But on August 18 of that year, a whopping 57 millimeters of ice melted away from the

base of the sheet. Notably, that day was smack in the middle of a six-day period that brought warm air and more than 80 millimeters of rain to the study site, says Christoffersen. Sensors showed that the temperature at the base of the ice sheet that day was 0.88°C , more than a degree warmer than the estimated -0.4°C melting temperature of ice at that depth.

So how did the base of the ice sheet get so warm? It probably wasn't because of the flow of heat upward through Earth's crust, which models suggest would have melted only 0.12 to 0.3 millimeters of ice that day. Instead, says Christoffersen, the likely culprit is the large amount of precipitation and surface meltwater pouring down through a natural hole in the ice called a moulin, which had coincidentally formed nearby.

These holes form when surface runoff collects in a deep crevasse and then gradually melts its way down, sometimes all the way to the bedrock. Moulins can be up to 10 meters in diameter and may serve as a meltwater superhighway for the rest of the melt season. Flow rates can be prodigious: the peak daily runoff in 2014 was an estimated 80 million cubic meters, about the same as the peak daily flow rate over China's Three Gorges Dam.

As water falls hundreds of meters down a moulin, it is heated by turbulence, friction, and the loss of potential energy. Friction, in particular, turns out to be an important heat source, says Christoffersen. "We've been ignoring this energy source for far too long," he says. "It's a substantial source of heat."

Once meltwater reaches the base of the ice sheet, it doesn't necessarily flow out immediately; instead, it can linger and influence glacial flow for weeks or months.

Christoffersen and another group of co-authors gathered salinity data from a fjord downstream of the study site in 2012 and 2017 and found that, even in wintertime, substantial volumes of meltwater flow into the fjord from beneath the glacier, thus freshening the normally salty water in the fjord (3).

This infusion of warm water at the base of Greenland's ice sheet can speed up the flow of its glaciers, says Christoffersen. Warm ice flows more readily than cold ice, and water enhances the flow by providing lubrication, akin to the thin film of water that forms beneath an ice skater's blades.

In 2018, Christoffersen and his colleagues observed the dramatic consequences of this effect (4). Pressure sensors on the bottom of a meltwater lake atop the Greenland ice sheet showed that in just 5 hours, almost 5 million cubic meters of meltwater drained from the lake and flowed through a moulin to the base of the ice sheet. The flow was so energetic that vibrations showed up on seismometers nearby. For a brief interval, the glacier's speed accelerated from 2 meters per day to about 5.3 meters per day. The researchers think that a better understanding of glacial lake drainage should improve predictions of how much meltwater might follow this route to the sea in decades to come. In the meantime, they say that the detrimental effects of glacial lake drainage on global sea levels are likely being underestimated in ice-loss models.

Besides not knowing how ice sheets will respond in the long term to water infiltrating their bases via moulins, cracks, and crevasses, it's also unclear how quickly they might respond to the loss of the buttressing effect of the ice shelves offshore when they collapse and float away, says Michael Oppenheimer, a climate researcher at Princeton University, NJ. "Things could fall apart faster than researchers think," he notes. "That's what gives us nightmares."

Coasts Are Not Clear

Ice-monitoring studies such as these are critical to understanding the scale of the challenge posed by sea-level rise in the future. According to the Intergovernmental Panel on Climate Change (IPCC), research largely based on simulations suggests that even if greenhouse gas emissions are reduced to zero by 2100, the melting of ice sheets and glaciers will drive a sea-level rise of about 43 centimeters, compared with the average level between 1985 and 2005 (5). In a future with largely uncontrolled greenhouse gas emissions, sea-level rise will be almost double that. Potentially catastrophic impacts would result, because coasts are home to about one-quarter of the planet's population and more than half of the world's megacities, which host dense populations and costly port facilities.

Uncertainties about how greenhouse gas emissions will change over the coming century, and how Earth's climate will respond to them, mean that the IPCC's estimates of sea-level rise could be off by up to 50%, says Oppenheimer. Moreover, he notes, ongoing changes in terrain at individual sites—such as sinking owing to subsidence, or uplift in the wake of glacial melt nearby—could either exacerbate or mask true sea-level rise.

Regardless of the true rate of sea-level rise, researchers note that there is already ample evidence that we need to start preparing for its effects as soon as possible. It can take decades to design, fund, and build projects to protect coastal infrastructure such as ports, bridges, and highways. And planners need to consider not only the average sea-level rise, but also the storm surges and other extreme events that will become more common in decades to come. "For some things," says Oppenheimer, "we should've started yesterday."

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