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Eos

SCIENCE NEWS BY AGU

The Mental Toll of Climate Change

Volcanoes on Venus

Dusting Off Climate Models

SPEEDING UP

THE SCIENCE OF ADVANCED ACCELERATION, FROM ICE BLOCKS TO BOW SHOCKS.

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The Fast and the Curious

This month, *Eos* takes a swift look at science and speed.

We start with "Redefining 'Glacial Pace,'" Damond Benningfield's report on how melting ice and retreating grounding lines contribute to (relatively) fast moving rivers of ice—in West Antarctica, glaciers are advancing up to 100% faster today than they were in the 1980s. It's all hands (and technologies) on deck to document and analyze the phenomenon, from remote sensing satellites to meters-deep ice cores, from airborne surveys to old-fashioned fieldwork. Read all about it on page 20, and check out more on grounding lines and glaciers on pages 8 and 16.

Our pace quickens considerably at the bow shock, where the supersonic solar wind meets Earth's magnetosphere, in "Space Raindrops Splashing on Earth's Magnetic Umbrella." Here, scientists Laura Vuorinen, Adrian LaMoury, Emmanuel Masongsong, and Heli Hietala outline the physics of fast plasma jets, and how these Earth-sized raindrops contribute to space weather (and safety). Learn more on page 34.

Finally, we consider how the urgency of the climate crisis has prioritized new approaches to health and well-being. In "The Mental Toll of Climate Change," Katherine Kornei shares how experts have identified a temporal spectrum of climate anxiety, ranging from the trauma of sudden-onset events to chronic fatigue associated with shifts in environmental constants. Individuals and communities have developed arrays of mental health resources and found that shared experiences have an unexpected outcome: "Health is the best communication pathway about climate change." Learn more on page 28.

Scientific discovery, climate change, and our responses to both are proceeding at breakneck speed. Buckle up!

Caryl-Sue Micalizio, Editor in Chief

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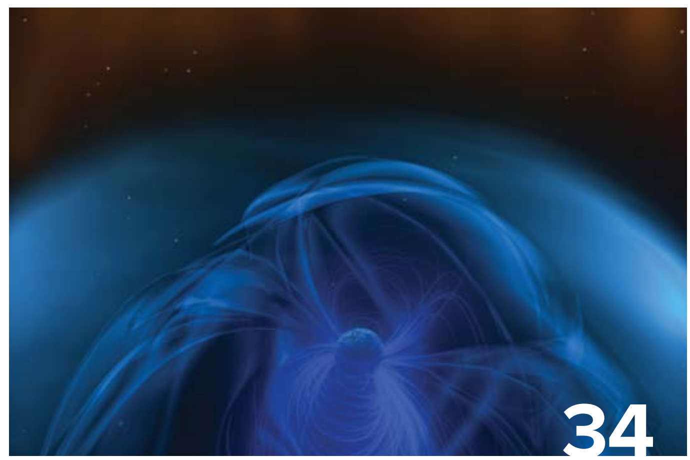
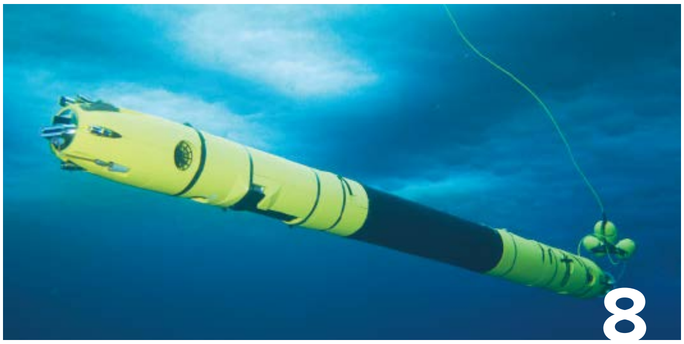
Randy Fiser, Executive Director/CEO

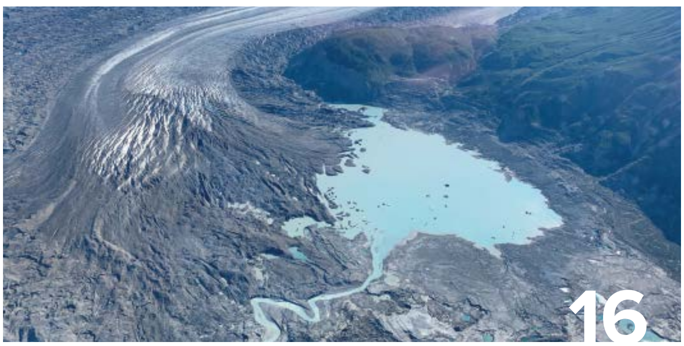


Features

On the Cover

The velocity of Nioghalvfjerdsfjorden Glacier in Greenland is affected by surface meltwater flow as well as seasonal ice fluctuation. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio





Columns

SMARTSOLO
SCIENTIFIC

Microseismic / Microtremor / Ambient Noise

The Most Reliable and Simple Scientific Instruments in Harsh Environment

Climate Models Aren't Dusty Enough

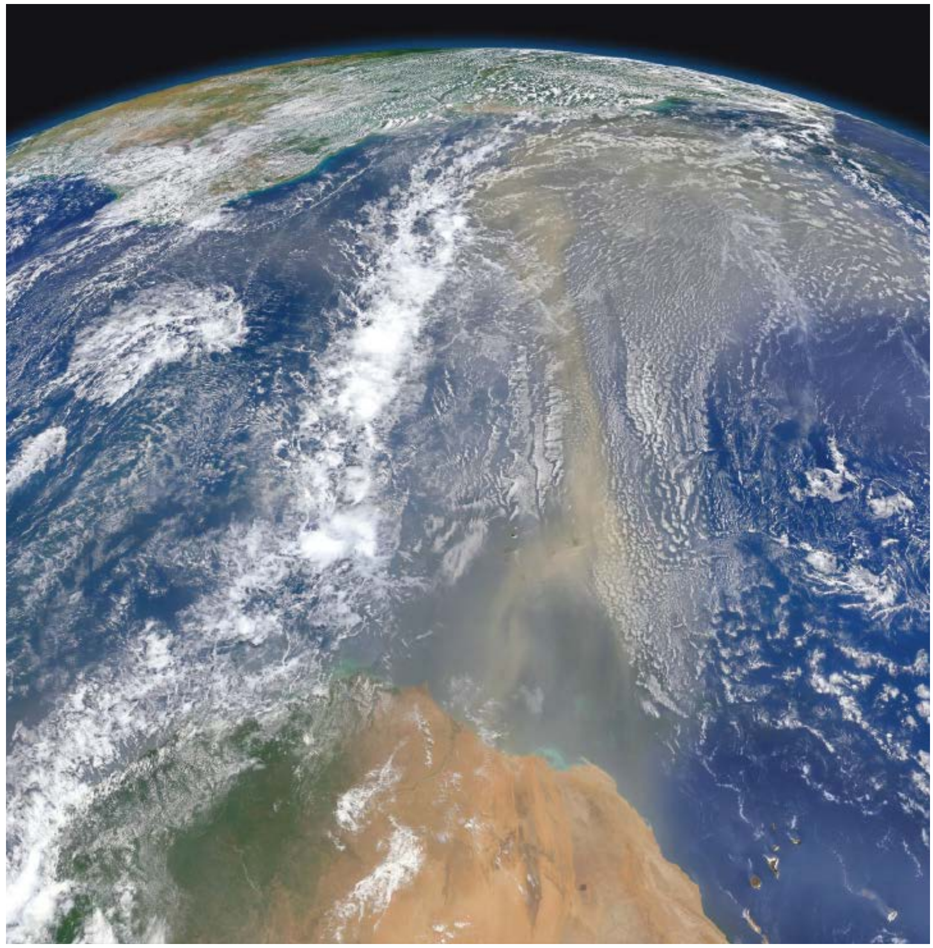
Greenhouse gas emissions are driving global warming, which scientists warn may soon pass 1.5°C relative to preindustrial temperatures. But rising mineral dust levels in the atmosphere are counteracting that warming to some extent, according to a study published in *Nature Reviews Earth and Environment* (bit.ly/dust-cooling).

"Models really struggle with getting the changes in dust," said University of California, Los Angeles atmospheric physicist Jasper Kok. "Part of that is just the physics of it is so complicated. It's also happening on very small scales that we don't resolve in models, and we don't have data for in models."

To reconstruct the history of mineral dust in the atmosphere, Kok and his colleagues compiled 25 records of dust deposition from around the world, including in ice core samples from Antarctica and lake bed sediments from North America. Their reconstruction also factored in the locations contributing the most dust, including Africa, the Middle East, central and eastern Asia, Australia, and North and South America.

Examining 150 years of atmospheric dust data, Kok and his coauthors found that airborne dust levels increased by around 55% between the mid-19th century and the 1980s and have largely held steady since.

To estimate mineral dust's net effect on climate, the researchers made use of climate and dust interaction models built on existing data from both satellites and ground-based photometers, which measure how much the Sun is blocked by airborne aerosols. That modeling is complicated and uncertain, Kok said, because of the complex ways in which dust appears to interact with other Earth systems, such as clouds.



Saharan dust blows toward South America in 2014. Credit: NASA

"Models really struggle with getting the changes in dust."

Floating dust grains act as seeds for ice crystals around which clouds can form. But different clouds have varied effects on cooling. Mixed-phase clouds, which are composed of both supercooled water droplets and ice crystals, are more likely to produce a cooling effect, whereas high, wispy cirrus clouds cause warming.

And then there are other aerosols in the atmosphere, particularly sulfates and nitrates from human-caused pollution. Previous research has shown that these pollutants have an even greater cooling effect than mineral dust, but dust helps pull many of those pollutants out of the atmosphere, Kok explained, creating a warming effect that most climate models do not account for.

Kok and his colleagues pegged the overall cooling effect of mineral dust at 0.25–0.07 watt per square meter. Because previous research has suggested that the atmosphere has warmed by 3–4 watts per square meter since the preindustrial period, dust has "masked" up to 8% of the global warming.

"That implies that the climate is just a little bit more sensitive to greenhouse gas warming than we thought," Kok said.

"If dust were to decline, it would speed up the warming further," he said.

Limited Dust Data Continue to Fuel Uncertainty

The uncertainty in dust's effect due to so many factors is made worse by the generally poor data Kok's study has had to rely on, according to Gisela Winckler, a paleoclimatologist at Columbia University. The study relied on 25 records of historic dust levels, and "that's very poor in coverage for when you try to do a global view of mineral dust," she said. "I have no doubt that this [analysis] is robustly done, but still, the underlying data sources are poor."

A major question is whether mineral dust levels will hold steady or decline. Changes in land use are known to create atmospheric dust problems on human timescales, such as the Dust Bowl that struck the United States in the 1930s, according to Paul Ginoux, a climate modeler with NOAA's Geophysical Fluid Dynamics Laboratory. But the data available are often too spaced out in time, he said. In the new study, the researchers "show an increase [in dust], but they totally missed the Dust Bowl."

Climate change itself may affect dust levels in multiple ways, such as through shifting wind patterns. "Wind strength has a lot to do with actually lofting that dust into the atmosphere," Winckler said. Climate scientists expect a warming climate to result in calmer winds, which could reduce the levels of dust blown aloft into the atmosphere.

The Future of Dust and Climate Studies

Kok, Ginoux, and Winckler each said that more data are needed to improve how climate models account for dust, and there are new opportunities to do just that. Ginoux is part of the science team for the Earth Surface Mineral Dust Source Investigation (EMIT), an instrument recently installed on the International Space Station to monitor dust levels in the atmosphere.

"Climate may be just a little bit more sensitive to greenhouse gas warming than we thought."

One of the takeaways of the study is the need to research mineral dust more locally, in the regions where it originates or could originate, because climate change itself changes local conditions, Kok said. "In California, this might be quite an important discussion, because the U.S. Southwest in general is expected to get drier" and therefore dustier. Kok and his colleagues recently began early work on a study of dust in California to report on "how that might change and what the implications could be. And maybe what policymakers could do about it."

By **Jon Kelvey** (@jonkelvey), Science Writer

Are There Active Volcanoes on Venus?

Often called Earth's sibling owing to its similar mass and size, Venus differs from our planet in a key way: Roughly 80% of its surface is made of volcanic rock. Despite a clear history of volcanism, only hints of current activity have been found, including relatively young lava flows and whiffs of volcanic gases in the atmosphere.

Now, researchers have identified what looks like an eruption that occurred 30 years ago, captured in images from NASA's Magellan spacecraft.

Old Data, New Discovery

Between 1990 and 1992, Magellan mapped the entire surface of Venus using synthetic aperture radar at a resolution of 100–300 meters (300–1,000 feet).

In a search of active volcanism, Robert Herrick, a planetary scientist at the University of Alaska Fairbanks, and Scott Hensley, a radar scientist at NASA's Jet Propulsion Laboratory, scoured the immense data set for surface changes in areas suspected to have ongoing volcanic activity.

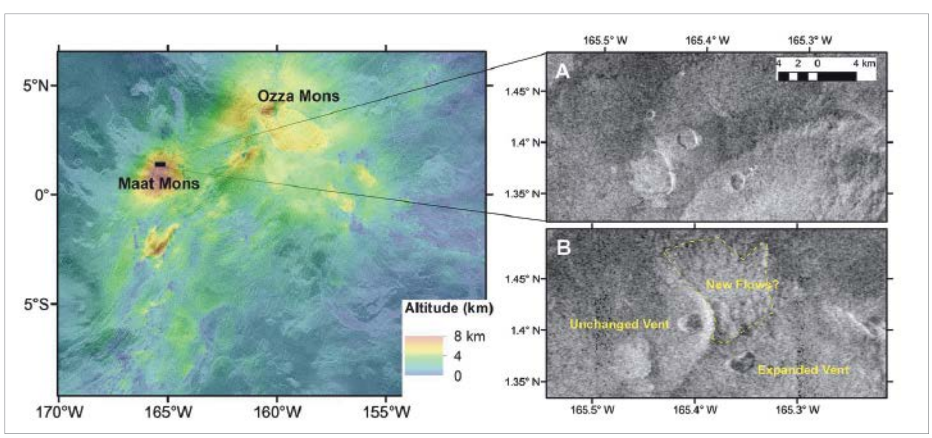
This search hadn't been done before because the task requires computing power and software that weren't available until recently. "Basically, you need to be able to load in a few hundred-gigabyte data sets and be able to pan around and zoom in and out," Herrick said. He compared the software they use to a planetary scientist's version of Google Maps. "That sort of software and hardware capability for someone using a desktop computer didn't really come into being until the last decade."

Magellan didn't make it easier on the researchers. The spacecraft recorded the images from a highly elliptical orbit, resulting in varying resolutions and observing angles. This lack of consistency made automated search processes almost unusable and forced the researchers to manually look for changes between images.

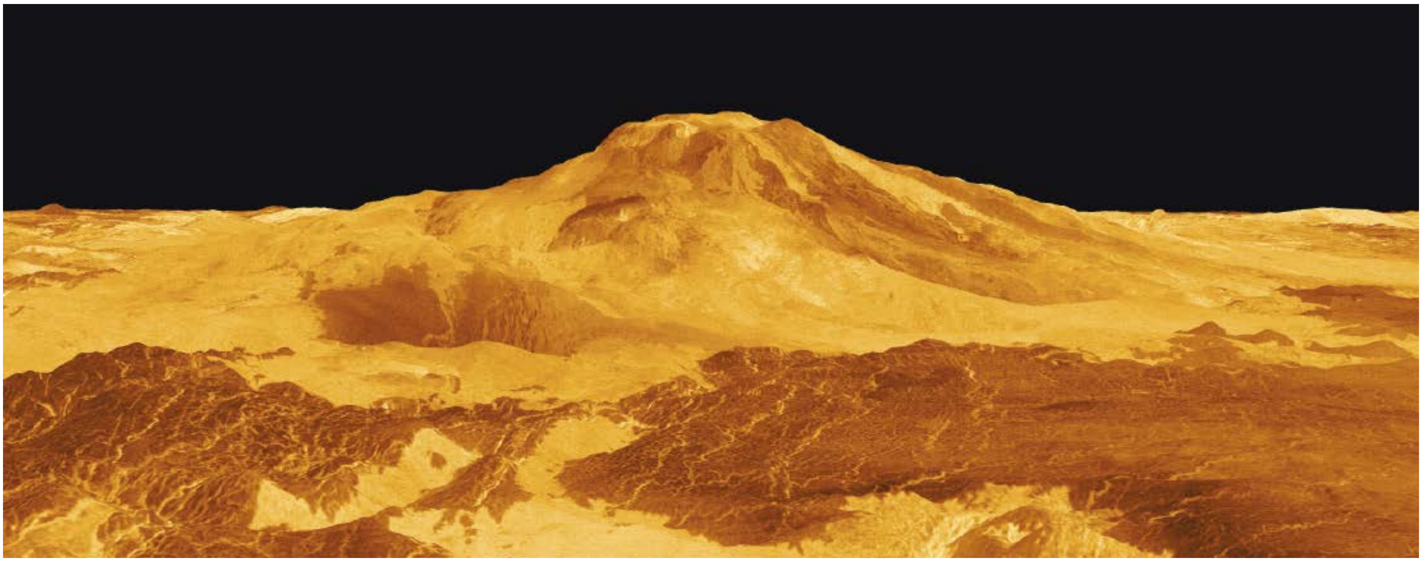
"We very strongly believe that we have a real change in the surface of Venus."

While zooming around the Venusian surface, the researchers looked for topographic changes between images acquired several months apart. Finally, they found a volcanic vent that clearly changed shape on the northern slope of Maat Mons, the largest volcano on Venus, with a total height of 9 kilometers (6 miles).

In the first image, the vent appears as a steep-walled circular pit around 175 meters (575 feet) deep, with an area of 2.2 square kilometers (roughly 0.8 square mile). In the second image, taken 8 months after the first, the vent had increased in size and become



The image at left shows the region of Maat Mons and Ozza Mons with altitude data overlaid. The image at right is the area of study, with the (a) earlier and (b) later images showing the expanded vent and the possible lava flows. Credit: Robert Herrick/UAF



Researchers created a 3D model of Maat Mons, a volcanically active region on Venus. Credit: NASA/JPL-Caltech

bean shaped, with a surface area of 4 square kilometers (1.5 square miles). It also looked as if the vent had been filled with an apparent lava lake, the researchers said.

Once Herrick and Hensley spotted the changes in the pit, they built 3D models of the feature to rule out a false positive caused by the varying perspectives of the different images. They used the relative positions of several features in the landscape to calculate the topography around the pit and give the images a viewpoint directly above the apparent volcano, making it easier to compare images.

Because the discovery "is the closest we've come to confirming something we've long assumed—and used as the rationale for new missions—[it's] a big deal."

They also simulated how the reconstructed feature would appear in radar observations, revealing that no perspective changes could explain the variation between the earlier and later images. "We concluded there's no way that the radar imaging geometry could account for the change in the imaging that we saw," Hensley said. "We very strongly believe that we have a real change in the surface of Venus."

The researchers presented their findings at the 54th Lunar and Planetary Science Conference on 15 March and in a study published in *Science* (bit.ly/Venus-volcano).

The images also revealed what appeared to be a newly emerged lava field downslope from the pit. Unfortunately, the area wasn't clearly visible in the first image because of the angle of the spacecraft when it was acquired, so it's possible this landform was already there in the first pass, the researchers said.

Even if lava didn't reach the surface, the clear change in the shape of a large volcanic pit is the first morphological evidence for ongoing volcanic or magmatic activity on Venus, said Paul Byrne, a planetary geologist at Washington University in St. Louis who wasn't involved with the study.

"It's entirely possible that magma moving in the subsurface could lead to the same result," Byrne said. "Think basically what happened at Kīlauea in 2018, when a body of magma moved downhill inside the volcano, erupting near the base, destroying homes, and leaving behind a much larger summit caldera. In my view, that's what's happened here on Venus."

The Smoking Gun

The dearth of impact craters on Venus suggests that the surface is strikingly young. For a long time, scientists assumed that the planet suffered some sort of cataclysm about 500 million years ago in the form of intense volcanism that rapidly resurfaced the whole planet, which then became geologically dormant.

But recent theories depart from this static view. Byrne and others have shown that the surface of Venus is covered by tectonic features—faults, folds, and fractures—that point to ongoing, albeit regional, processes.

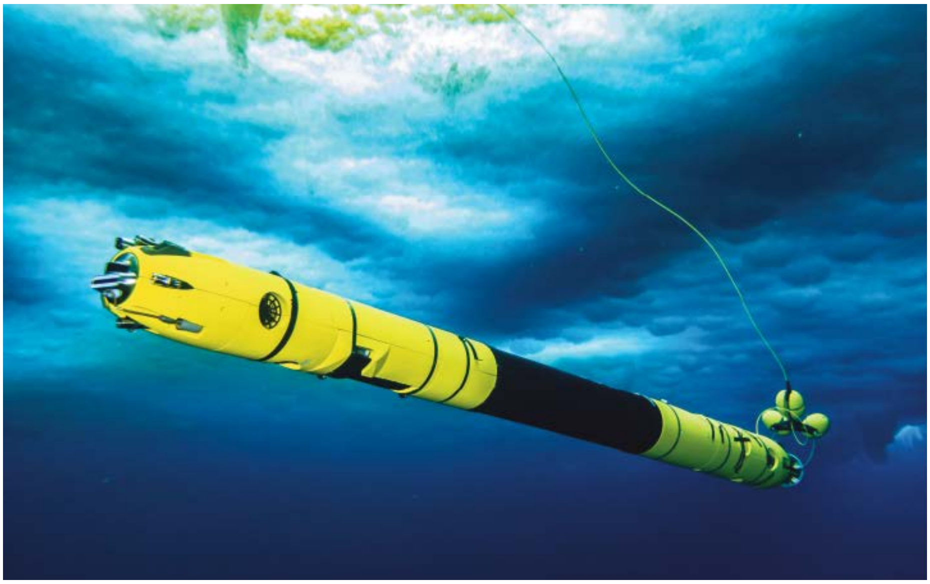
Because Venus lacks plate tectonics, these processes could be driven by mantle convection, which forms mantle plumes similar to those that power hot spot volcanism on Earth in places far from plate edges, such as Iceland and Hawaii.

"The reason this finding is important is because although there is lots of circumstantial evidence for ongoing volcanism, we've never seen a 'smoking gun,'" Byrne said. Because the discovery "is the closest we've come to confirming something we've long assumed—and used as the rationale for new missions—[it's] a big deal."

"Studying Venus and unlocking new findings about its evolution can help us understand our own home," said Lori Glaze, NASA's Planetary Science Division director. "The more we learn about the characteristics of the planets in our backyard, including Venus, the more we can apply to understand distant exoplanets," she added.

By **Javier Barbuzano** (@javibarbuzano), Science Writer

“Icefin” Investigates a Glacial Underbelly



Icefin, a submersible designed to explore icy environments, cruises under the McMurdo Ice Shelf in Antarctica. Credit: Rob Robbins/NSF

Thwaites Glacier, infamous for its potentially outsized contribution to sea level rise, recently got its close-up. Researchers maneuvered a robot under Thwaites's floating ice shelf and collected data about the Antarctic glacier's so-called grounding line—the region where its ice first lifts off solid land. The new results revealed that enhanced melting occurs in places where Thwaites's underbelly is particularly sloped and that water stratification helps to inhibit melting overall.

Reuniting with the Robots

In October 2019, Britney Schmidt, an Earth and planetary scientist then at the Georgia Institute of Technology in Atlanta, and her collaborators embarked on a multiday journey by plane to McMurdo Station, a research base in Antarctica operated by the United States. There, they met up with colleagues, tried their best to acclimate to the perpetual daylight of polar summer, and reunited with two very precious pieces of cargo.

The researchers had brought with them a pair of 3.5-meter-long robots. Known as Icefins, each bright yellow, pencil-shaped submersible was kitted out with instruments ranging from cameras to sonar to temperature and salinity sensors. Icefin is like a robotic oceanographer, said Schmidt, who led the sub's development and is now at Cornell University in Ithaca, N.Y.

The submersible's long, thin profile made it well suited for maneuvering under ice, which is why Schmidt and her colleagues went to Antarctica to study Thwaites, a Florida-sized expanse of ice in West Antarctica that's recently been melting at an alarming rate. The unstable nature of Thwaites, paired with its sheer volume—the water contained within it would raise global sea level by more than half a meter—has made it the target of a massive research effort that includes the project that brought Schmidt and her collaborators to Antarctica: Melting at Thwaites Grounding Zone and Its Control on Sea Level (MELT) project.

After spending several months thoroughly testing the two Icefins on the McMurdo Ice Shelf, Schmidt and some of her colleagues departed for Thwaites with one of the robots in tow. Working in temperatures as low as −30°C, the researchers set up camp on the eastern part of the glacier's ice shelf, roughly 2,000 kilometers (1,200 miles) from McMurdo.

Their home away from home consisted of a line of brightly colored pyramid-shaped tents—so-called Scott tents, named for the explorer Robert Falcon Scott—for sleeping in, a larger tent that could hold the entire group for meals and socializing, a drilling rig, and a dome-shaped tent that doubled as a scientific control room.

Like Hot Water Through Ice

Shortly after the New Year, the team began drilling. Using hot water, they bored through the full thickness of Thwaites's ice shelf—587 meters (0.4 mile)—until they reached water. That process took roughly 24 hours. Schmidt and her colleagues then carefully lowered the Icefin down with just centimeters to spare around the robot. Roughly an hour later, when the Icefin's sensors indicated that it had entered the Amundsen Sea, the team turned the robot toward the continent to seek uncharted territory.

For glaciers such as Thwaites that terminate in the ocean, some of their bulk rests on land and some floats on the water. The transition is known as the grounding zone or grounding line. “That's a really important place because it's…where the ice hits the

The team set up Scott tents on Thwaites Glacier. Credit: Icefin/ITGC/Dichek water for the first time," Schmidt said. Even water that's only a few degrees above freezing can transfer enough heat to ice to kick-start melting, she explained.

But accessing the grounding line is notoriously tough—a glacier's floating portion can extend for tens or even hundreds of kilometers beyond the grounding line, so exploring from the ocean side often isn't practical. "It's one of the hardest places to go look," said Alastair Graham, a marine geophysicist at the University of South Florida who was not involved in the new research. Graham and his colleagues have studied how Thwaites's grounding line has shifted position over time by analyzing the imprints it's left behind in the seafloor.

"Until Thwaites, we had no data from the grounding line of any major glacier," Schmidt said. "We were trying to get the very first data from this environment."

Right up to the Edge

After maneuvering Icefin inland for a little over a kilometer (0.6 mile), the MELT team sent the robot to within a few centimeters of Thwaites's grounding line.

They discovered that the ice in the region was heavily scalloped and pitted with crevasses up to tens of meters deep. That was a big surprise, Graham said, because ice shelves long have been thought to be flat or gracefully sloping. "If you look at people's drawings of grounding zones, they rarely have crevasses."

The team furthermore found that ice at the grounding line was melting at different rates: Steeply sloped ice faces such as crevasse walls tended to melt much more rapidly than flatter ice faces. Only about 10% of Thwaites's base is steeply sloped, but those regions account for 27% of ice loss, Schmidt and her colleagues reported in a paper published in *Nature* (bit.ly/Thwaites-staircase).

"Until Thwaites, we had no data from the grounding line of any major glacier."

That difference likely arises because of water stratification, the researchers concluded. Colder, fresher water tends to linger above warmer, saltier water near the undersides of glaciers. Flatter ice faces are therefore mostly bathed in colder water, but steeply sloped ice faces are exposed to both colder and warmer waters.

Icefin also measured stronger water currents in crevasses, which might also play a role in transferring heat to the ice, the team suggested. That's because stronger currents can disrupt water stratification.

"You can imagine pouring your milk into your coffee and stirring it and seeing the billows and filaments," said MELT team member Peter Davis, a physical oceanographer with the British Antarctic Survey in Cambridge, U.K. That mixing essentially removes the insulating layer of cold water that normally lingers near a glacier, explained Davis.

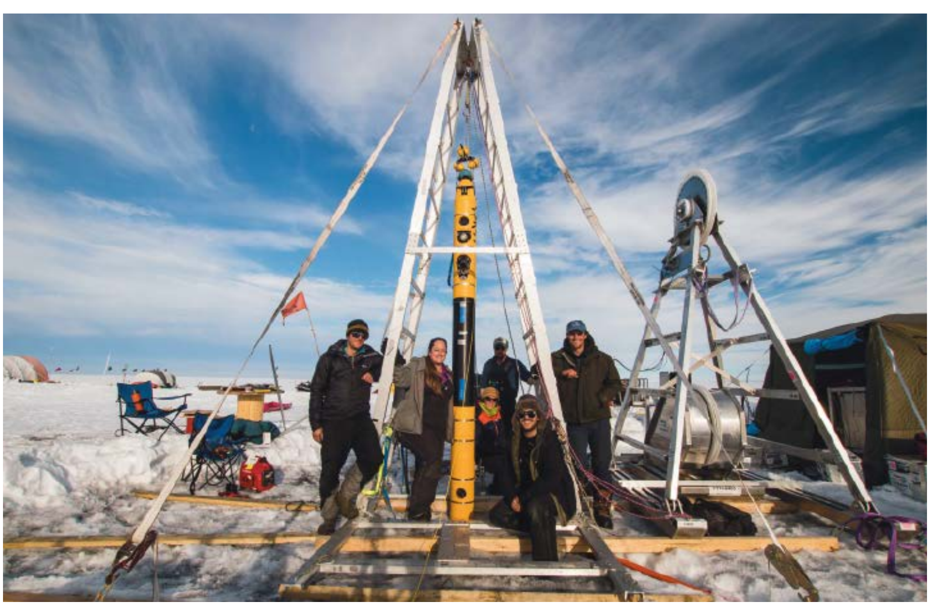
However, Davis and his colleagues calculated that overall, the underside of Thwaites is melting far less rapidly than predicted by models. That might sound like good news, Davis said, but the fact remains that the glacier is still retreating. "What this shows us is that the retreat is being driven by a lower rate of melting than perhaps we expected."

That observation sends scientists back to the drawing board to better understand what's primarily responsible for Thwaites's observed retreat, he said. Davis and his colleagues also reported their results in *Nature* (bit.ly/Thwaites-melting).

It will be interesting to continue to monitor Thwaites, Graham said. There's a chance that the glacier's lower melt rate will translate into slower retreat in the future, he added, and Thwaites is definitely a glacier to watch. "I don't think we should leave it alone."

By **Katherine Kornei** (@KatherineKornei), Science Writer

Icefin was pulled back up to the surface through a borehole drilled into Thwaites Glacier. Credit: Icefin/ITGC/Schmidt



Researchers James Wake, Britney Schmidt, Catrin Thomas, Paul Anker, Dan Dichek, and Andy Mullen pose with an Icefin robot on Thwaites Glacier in Antarctica. Credit: Icefin/ITGC/Dichek

Tonga Eruption May Temporarily Push Earth Closer to 1.5°C of Warming

When Hunga Tonga–Hunga Ha'apai (HTHH) erupted in January 2022, it shot the standard volcanic cocktail of ash, gas, and pulverized rock into the sky. But the eruption included one extra ingredient that's now causing climate concerns: a significant splash of ocean water.

The underwater caldera thrust 146 metric megatons of water into the stratosphere, potentially contributing to atmospheric warming over the next 5 years, according to a new study published in *Nature Climate Change* (bit.ly/Tonga-eruption-temps).

The new study showed that the warming caused by the HTHH eruption escalated the likelihood of Earth tipping past the 1.5 degree temperature increase targeted by the Paris Agreement. In May 2022, the WMO announced there was a 50% chance of exceeding the 1.5 degree threshold over the next 5 years; the HTHH eruption may have increased that probability by 7%.

Straight to the Stratosphere

Explosive volcanoes inject ash and sulfur dioxide into the atmosphere, typically leading to global cooling. Mount Tambora's sulfur dioxide plume in 1815, for example, inhibited sunlight from reaching Earth, triggering the "year without a summer."

The HTHH eruption was unusual. Unlike other eruptions its size, HTHH had a relatively low sulfur dioxide content. Researchers assumed it led to only 0.004°C of global cooling in 2022.

"If we're only a quarter of a degree from 1.5°C, those four hundredths of a degree do actually make a tangible difference."

HTHH also exploded just below the ocean surface, injecting vaporized seawater into the stratosphere like a syringe. Though seemingly innocuous, water vapor is the planet's most common greenhouse gas. Whereas volcanic sulfates commonly block sunlight from reaching Earth, water vapor keeps it from leaving.

The HTHH blast sent water vapor and other gases to at least 40 kilometers (25 miles) above Earth's surface and punched through the boundary of the stratosphere. In this atmospheric layer, cool, heavy air rests below less dense warmer air. Because there is little turbulence to stir the system, "you can get a perturbation lasting for, in an atmospheric sense, quite a long time," said Stuart Jenkins, an atmospheric physicist at the University of Oxford and lead author of the new study. The eruption boosted the water vapor content of the stratosphere by 10%–15%, according to the study.

Using reconstructions of global climate, Jenkins and his colleagues established the monthly baseline conditions for the 7 years prior to the eruption, then simulated the effect of water vapor in the stratosphere for 7 years after the event. The researchers assumed that the injected water vapor would settle out of the stratosphere in that time. Their model parameters were conservative, Jenkins said, and assumed the volcanic plume spread widely between altitudes and latitudes.

The volcanic ash plume from the Hunga Tonga–Hunga Ha'apai eruption sent water vapor into the stratosphere. Credit: NASA Earth Observatory

The model calculated the monthly change in Earth's energy balance caused by the eruption and showed that water vapor could increase the average global temperature by up to 0.035°C over the next 5 years. That's a large anomaly for a single event, but it's not outside the usual level of noise in the climate system, Jenkins said. But in the context of the Paris Agreement, it's a big concern.

"If we're only a quarter of a degree from 1.5°C, those four hundredths of a degree do actually make a tangible difference," he said. The planet was already 50% likely to warm past 1.5°C in the next 5 years, and the presence of HTHH's water vapor increased the odds of temporarily exceeding that threshold to 57%, according to the simulation.

What About 1.5°C?

The volcano launched an "unprecedented" amount of water vapor into the stratosphere, said Patrick Sheese, a climate physicist at the University of Toronto who was not involved in the study. But the event's impact can't compare with that of human emissions, he said. Even if the eruption increases temperatures as the simulation predicted, that's only a small, temporary lift toward the 1.5°C threshold.

Decades of research have shown that humans are still responsible for most of the warming.

The study "is just another reminder that nature isn't going to help us out of climate change."

But as the study showed, part of that warming will have been caused by natural anomalies. Any number of phenomena can sway global temperatures, from El Niño conditions in the Pacific Ocean to wildfires in Siberia.

The HTHH eruption may nudge the temperature past 1.5°C of warming, but that doesn't mean the Paris Agreement has failed; the event demonstrated how close the world is to its agreed-upon tipping point.

The study "is just another reminder that nature isn't going to help us out of climate change," Sheese said. "This clearly is up to us to fix."

By **J. Besl** (@J_Besl), Science Writer

We (Probably) Can't Tell Whether Mars Has Life

The Perseverance rover snapped a photo of an escarpment known as "Scarp a" in Jezero crater. Credit: NASA/JPL-Caltech/ASU/MSSS

Many features on the surface of Mars look similar to features right here on Earth—from towering volcanoes to weathered rock outcrops to clear traces of dried-up lakes and riverbeds. The similarities have led many—including noted space oddity David Bowie—to ask, Is there life on Mars?

Although robotic landers have found evidence for water and organic molecules, the answer so far seems to be no. A study published in *Nature Communications,* however, may give reason to hope the issue isn't settled (bit.ly/detecting-life-Mars). Researchers showed that even with the most advanced laboratory equipment we have, it's difficult to identify life on Earth, much less on another planet.

"It will be harder than expected to find evidence of life on Mars with the current generation of instruments that we're sending," said Armando Azua-Bustos, a microbiologist at Saint Louis University Madrid in Spain and lead author of the study.

Azua-Bustos and his collaborators concluded this from experiments performed in the Red Stone region of the Atacama Desert in Chile. As the oldest and driest desert on the planet, the Atacama is frequently cited as the closest terrestrial analogue to Mars. The Red Stone region is an ancient alluvial delta (between 100 million and 163 million years old) that bears strong geological similarities to the 3.5-billion-year-old delta at the edge of Jezero crater on Mars, where NASA's Perseverance rover now is collecting samples.

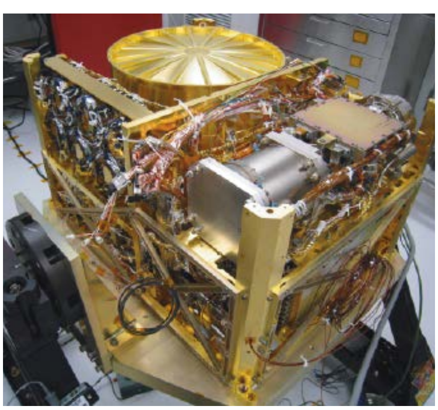
The Right Equipment

In practice, searching for life involves chemical experiments, such as gas chromatography-mass spectrometry (GCMS), in which Martian soil samples are vaporized and their components are analyzed for organic molecules or chemicals known to be inimical to known life. Many planetary missions have carried GCMS instruments, including the 1970s Viking landers on Mars, the Cassini Saturn orbiter—which found organic molecules in jets of water from the moon Enceladus—and the currently operating Martian rovers, Curiosity and Perseverance.

No, this isn't Mars. The Red Stone alluvial delta site in Chile's Atacama Desert strongly resembles the edge of Jezero crater on Mars. Credit: Armando Azua-Busto

NASA's Perseverance rover is currently exploring Jezero Crater (shown here) with a suite of scientific instruments designed to detect evidence of ancient life. Credit: ESA/DLR/FU-Berlin

Azua-Bustos and his colleagues used GCMS, DNA/RNA sequencing, and optical microscopes to search for evidence of both living and fossil microorganisms in Red Stone rocks. The GCMS they used was more sensitive than anything carried on Mars missions, yet it detected only trace evidence of life.



The Sample Analysis at Mars (SAM) instrument inside the Curiosity rover includes a gas chromatograph–mass spectrometer, which analyzes soils collected from the surface. Credit: NASA-GSFC

In addition, the genetic sequencing—which Mars landers currently are not capable of—couldn't identify 9% of the organisms at all and could make only broad classifications for an additional 40% of the samples. The researchers referred to these unidentified organisms as the dark microbiome, which may be analogous to any Martian life scientists might find, if it resembles life on Earth at all.

Amy Williams, an organic geochemist at the University of Florida who was not involved in the study, said future planetary missions would need broader approaches like those used at the Red Stone site. "The next step is to do an extraction on [Martian] samples to pull the organics out and concentrate them," she said. "That's what we do on Earth with very lean samples that don't have a lot of organics in them."

Both Azua-Bustos and Williams, who works on the Curiosity rover and the design of the proposed Mars Life Explorer, emphasized the need to return Martian samples to Earth for analysis because laboratories here will always be more advanced than anything we can send on a spacecraft.

"For me, the easiest way is to see something crawling, but that probably will not be the case.

Even confirming fossil microbes on Earth is fraught, Azua-Bustos pointed out. "I would expect that it will be even harder on Mars to see anything, given the extreme environment," he said. "For me, the easiest way is to see something crawling, but that probably will not be the case."

By **Matthew R. Francis** (@DrMRFrancis), Science Writer

Marauding Moons Spell Disaster for Some Planets

Roughly half of all stars have planets orbiting them, scientists currently believe. And surely many have moons, too, if our own solar system is any indication (only Mercury and Venus lack them).

Now a researcher has shown that the presence of a moon might be a planetary liability: It may escape the gravitational tug of its host planet only to crash back into it, potentially obliterating any life present. Such a marauding moon would leave an observational fingerprint—copious amounts of dust produced in the impact—that would glow in infrared light and be detectable with astronomical instruments, the researcher suggested. These results were published in *Monthly Notices of the Royal Astronomical Society* (bit.ly/marauding-moons).

Theory suggests that moons in other solar systems, as suggested in this artist's illustration, might occasionally collide with their host planets. Credit: iStock.com/dottedhipp

Moons Across the Milky Way

Astronomers think that solar systems are born from spinning clouds of gas and dust. Over time, that primordial material coalesces into larger bodies, which go on to collide with one another, forming planets and moons.

According to that traditional picture, moons should be commonplace, said Joan Najita, an astronomer at the National Optical-Infrared Astronomy Research Laboratory in Tucson, Ariz., not involved in the new research. "A moonlike object seems like a pretty natural outcome."

Several years ago, motivated by the notion that exomoons ought to be prevalent in the Milky Way as well as puzzling observations of excess infrared emission around some middle-aged stars, Brad Hansen began thinking about how the presence of a moon might affect its host planet.

"A moonlike object seems like a pretty natural outcome."

But Hansen, a planetary scientist at the University of California, Los Angeles, wasn't thinking about run-of-the-mill effects of moons, such as the tides they induce on a watery planet. Instead, he was curious about the possibility of a collision between a moon and its host planet and the likelihood that such an event, were it to occur, might be detectable with large research telescopes.

The Retreat of the Moon

The orbit of our own Moon is changing, albeit very slowly; every year, the Moon moves about 4 centimeters (1.5 inches) farther away from Earth. Gravitational forces are the culprit—the Moon tugs on Earth gravitationally, causing the planet to bulge toward the Moon, and because the rotation of our planet moves that bulge ahead of the Moon by roughly 10°, our satellite essentially feels an extra pull forward. The Moon consequently speeds up and, according to the tenets of orbital mechanics, moves outward in its orbit. At the same time, Earth's rotational period is also slowing down because of conservation of angular momentum. "The Moon is spiraling out just because it's extracting angular momentum from the spin of the Earth," Hansen said.

Hypothetically, the Moon's orbit will continue to enlarge, and Earth's rotational period will continue to slow in tandem for tens of billions of years. (That's notwithstanding, of course, other more pressing cosmic eventualities, such as the death of the Sun and its probable engulfment of Earth in roughly 5 billion years.) But moons orbiting planets that are substantially closer to their host stars could undergo a much different course of evolution, Hansen calculated.

With an eye toward determining the long-term outcomes of planetary systems containing moons, Hansen modeled a solar system containing a single spinning rocky planet up to 10 times the mass of Earth with a rocky moon that ranged in mass from 1 to 10 times the mass of Earth's Moon. In various model scenarios, he assumed that the planet was anywhere from 0.2 to 0.8 astronomical unit from its host star. For comparison, Earth orbits the Sun at a distance of 1.0 astronomical unit, or roughly 150 million kilometers (93 million miles).

Crossing a Boundary

Hansen modeled the gravitational interactions of the moon, planet, and star in each planetary system. He found that for planets orbiting between roughly 0.4 and 0.8 astronomical unit from their host stars, their moons tended to spiral outward, just as our own Moon is doing.

But when Hansen modeled the long-term evolution of those out-spiraling moons, he found that some of them traveled so far from their host planet that they ended up crossing an invisible boundary: the edge of a volume of space known as the Hill sphere. Within a planet's Hill sphere, an orbiting object primarily feels that planet's gravity and is therefore gravitationally bound to it. The Moon and all of our planet's artificial satellites are within Earth's Hill sphere, which extends roughly 1.5 million kilometers (900,000 miles) into space.

A moon that journeys beyond a planet's Hill sphere is no longer bound to that planet—instead, it now orbits the star in its planetary system. However, it's still in proximity to its erstwhile host, which makes for a gravitationally unstable situation, said Hansen.

Hallmark of a Cataclysm?

Hansen showed that such moons overwhelmingly went on to collide with their host planets several hundreds of millions or even a billion years after the formation of the planetary system. Such collisions would, in all likelihood, be catastrophic impacts, he estimated, and they'd release copious amounts of dust. That material would then be heated by starlight to temperatures of several hundred kelvins and would accordingly begin to glow in the infrared. That makes sense, said Najita. "It sounds quite plausible."

Perhaps these marauding moons could explain why some middle-aged stars show a significant excess of infrared emission, Hansen postulated. Planetary systems should be generally pretty settled places—in terms of giant impacts—after 100 million or so years, he said, so spotting what's likely a lot of dust is puzzling. Maybe astronomers are seeing the hallmarks of a cataclysm in dust-enshrouded star systems, Hansen hypothesized.

But there are other ways to explain particularly dusty stars, said Carl Melis, an astronomer at the University of California, San Diego not involved in the research who studies stars that show excess infrared emission. Melis and his colleagues have suggested that collisions between planets, not between planets and moons, are responsible for creating the dust visible around some stars. One way to discriminate between those two scenarios, he said, is to look for planets orbiting those stars. Consistently finding several planets would lend credence to his hypothesis, he said, but finding only one would bolster Hansen's viewpoint. "It's very testable."

By **Katherine Kornei** (@KatherineKornei), Science Writer

Ice Cores Record Long-Ago Seasons in Antarctica

To many, the Antarctic Ice Sheet is a blank, frozen wasteland. But to those who study Earth's past climate, it contains a wealth of information. Gas bubbles trapped in ancient ice preserve long-ago atmospheres, and chemical changes in the ice trace fluctuations in Earth's temperature.

Climate scientists have used these "ice core diaries" to reconstruct long-term trends in Earth's temperature, such as the comings and goings of ice ages. But so far, it has been difficult to obtain long-term records of a hot-and-cold pattern that is more familiar to us: the seasonal cycle.

Ice doesn't reveal its secrets easily.

In January, a team of scientists presented a seasonal temperature record dating back 11,000 years. The ice revealed a connection between intense solar radiation and hot summers in Antarctica.

"[This] is the first record of its kind," said Tyler Jones, a polar climatologist at the University of Colorado Boulder's Institute of Arctic and Alpine Research (INSTAAR) and lead author of the study (bit.ly/ice-core-temps). Seasonal temperature data help researchers understand Antarctica's natural rhythm, which is critical for anticipating the region's responses to warming.

Temperatures in the Time of Mammoths

Researchers can infer past temperatures by measuring the ratios between isotopes—atoms with the same number of protons but different numbers of neutrons. Because hydrogen is a main constituent of water, paleoclimatologists often focus on the ratio between common hydrogen and its heavier sibling, deuterium: The warmer the regional average temperature was when the ice formed, the higher the deuterium concentration is.

By measuring the relative abundances of common hydrogen and deuterium along 3,405 meters (11,171 feet) of the West Antarctic Ice Sheet Divide core (WDC), Jones and his coauthors reconstructed temperatures into the early Holocene, a time when humans were just starting to develop agriculture and mammoths still roamed Siberia and North America.

The data showed that summer temperatures in West Antarctica were higher when the region received a more intense dose of sunlight. This deceptively simple observation is connected to Milankovitch cycles, a major tenet of climate science. According to Milankovitch theory, the amount of sunlight reaching Earth's surface—which depends on Earth's rotation and orbit around the Sun—drives long-term climate change. The study validated the link between sunlight and climate on a seasonal scale: Intensely sunny summers lead to warm temperatures that can potentially trigger large-scale melting of ice.

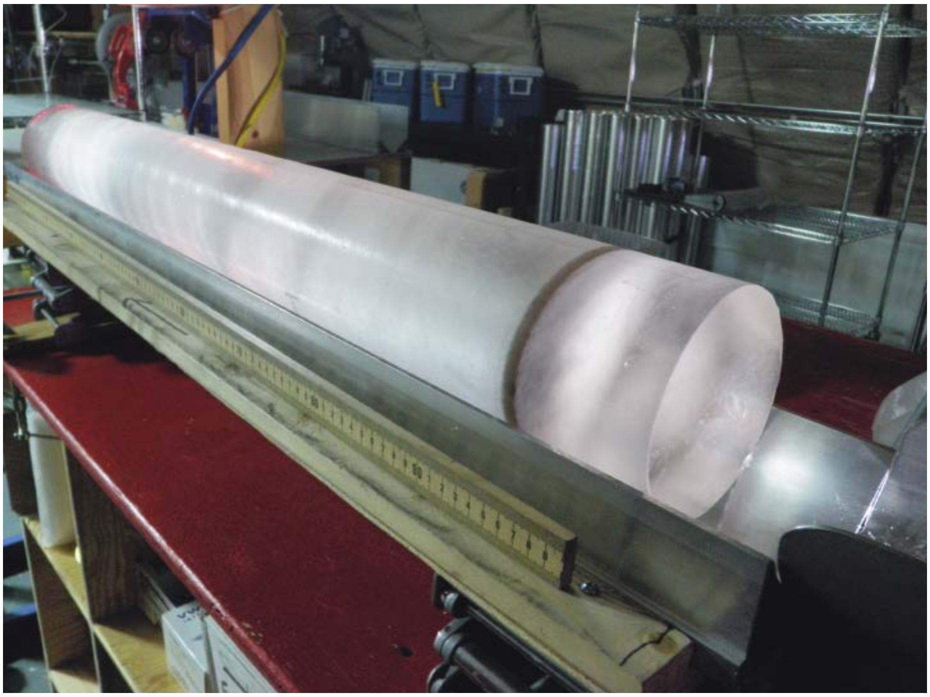
Deciphering Ice Core Diaries

Ice doesn't reveal its secrets easily. To construct a continuous temperature record, the scientists needed to be reasonably sure the ice core didn't contain any significant gaps: A long period without snowfall can create gaps in the information stored inside.

Zeroing in on seasonal cycles requires ice deposited in different seasons to be distinguishable within the ice core. Imagine trying to identify the layers of a tiered cake 11,000 feet tall—a challenging task in any case, but impossible if the layers are too thin to be differentiated. The WDC was ideal for seasonal measurements because its ice accumulated quickly, producing annual layers 10–50 centimeters (4–20 inches) thick.

The researchers measured water isotopes at 5-millimeter (0.2-inch) intervals along the ice core. Because each of those intervals represented several weeks' worth of ice, the resulting temperature record resolved seasonal changes. The researchers compared the data with the amount of sunlight that reached the pole, determined using numerical models.

Even an ideal ice core can be difficult to decipher, though. The researchers had to account for uneven snowfall between seasons, sporadic storms, and natural diffusion of water particles in ice. Correcting for diffusion and natural noise was a long-haul effort that required "working through a mountain of modeling and statistical considerations," said Jones, who began contributing to the project as a doctoral student in



An ice core from the West Antarctic Ice Sheet Divide is giving scientists a glimpse of the continent's seasonal temperatures across millennia. Credit: Heidi Roop/NSF

2013. "It is both a celebration, and certainly some relief, seeing our results published."

The results have garnered interest from ice core researchers, some of whom questioned whether the group's statistical methods were sufficient to tease out seasonal patterns from the ice. Nevertheless, Christo Buizert, a paleoclimatologist at Oregon State University who was not involved with the research, called it "one of the most convincing studies to date to resolve both the summertime and wintertime temperatures from a single location."

The Antarctic record of small-scale temperature fluctuations feeds into what we know—and don't know—about Earth's climate. Seasonal differences are especially relevant in polar regions, where warm summers melt the ice, Buizert explained. "Snow and ice care about the summer temperature, not the annual mean temperature, so having seasonally resolved temperatures is really exciting."

"Snow and ice care about the summer temperature, not the annual mean temperature."

By enabling researchers to connect cause and effect—as with sunlight and summer temperatures—seasonal records can offer deep insights into climate patterns. Jones said he hopes the research will inspire similar studies on other ice cores: "We could learn a lot from focusing on seasonal climate in the future," he said, "provided such records can be obtained."

By **Caroline Hasler** (@carbonbasedcary), Science Writer

Lakes Can Change How Glaciers Move

At the feet of mountain glaciers, melting ice forms pools of water that can be trapped behind moraines. And with warming temperatures, these pools are surging in both size and number. In Alaska and northwestern Canada, 183 new lakes appeared between 1984 and 2019, covering 483 square kilometers (190 square miles) in total.

New research showed that the presence of these proglacial lakes affects how quickly their parent glaciers retreat (bit.ly/proglacial-lakes).

"We kind of knew that there's this interplay between glaciers and proglacial lakes, but we're just scratching the surface of that understanding."

Melting mountain glaciers are responsible for about a third of global sea level rise. Scientists need a better understanding of how the movement of glacial ice is going to change in a warming and potentially wetter world, said Brittany Main, a doctoral candidate in geography, environment, and geomatics at the University of Ottawa in Canada and lead author of the study.

"We kind of knew that there's this interplay between glaciers and proglacial lakes, but we're just scratching the surface of that understanding," Main explained. To better understand the link, she and her colleagues examined 120 years of historical photographs and used satellite images, field visits, and air surveys of Kaskawulsh Glacier in Canada and the lakes found at its foot.

Ice in the Balance

Though researchers have had a hunch that a lake in front of a glacier likely affects velocity, finding locations to study the interaction has been difficult, Main said. Records show that between 1899 and 2020, the lakes below Kaskawulsh Glacier appeared, disappeared, and reappeared, providing a unique set of circumstances to address the problem. "We really got to watch it go through this cycle," she said.

As Kaskawulsh Glacier retreated in the first half of the 20th century, two proglacial lakes formed.

By the summer of 2015, one of them, Slims Lake, had grown to 3.7 square kilometers (1.4 square miles). But in the spring of 2016, it suddenly drained, its surface level falling by 17 meters (56 feet, or 30%). The toe of the glacier, which had been floating in the lake, dropped onto the sediment along the new shoreline. The researchers saw that the event slowed the glacier's velocity by almost 50%—a big impact considering that only one of the glacier's two proglacial lakes drained.

"A really cool and novel aspect of this research is they can essentially use this lake drainage on Slims Lake as a natural experiment," said William Armstrong, a glaciologist at Appalachian State University who was not involved in the research. The ability to track the glacier-lake relationship over a long time allays concerns about unaccounted-for variables, he added.

The impacts of proglacial lakes on overall glacier health and the degree to which lakes might be driving ice loss in a warming climate remain unclear. "I think that's still an open question about this glacier and the effect of these lakes as a whole," Armstrong said.

Environmental Impacts Beyond the Glacier

The drainage of Slims Lake in 2016 brought local environmental repercussions as well. After the event, enormous dust storms blew through local communities almost every day because sediment once underwater had been exposed. The water in the lake that once flowed into the Ä'äy Chù (Slims River) was rerouted into the Kaskawulsh and Alsek rivers. That, in turn, affected ice stability, regional drainage, fish populations, and sediment transport.

As the climate warms and melting glaciers feed ever growing proglacial lakes, the risk of outbursts—caused by a failure in the lake wall—or rapid drainage increases. The 20th century saw a sixfold increase in glacial lake outburst floods, which can happen very quickly, killing people and destroying infrastructure and land. One estimate put 15 million people at risk of future outburst floods.

Less Stability

Kaskawulsh Glacier is also an inherently less stable glacier because some of it sits on a reverse slope—the bedrock underneath curves up toward the toe of the glacier like a skateboard ramp. The ice fills a deeper space farther upstream and is therefore thicker than it would be on a normal slope. That, in turn, means that as the glacier retreats, more

Slims Lake is nestled at the snout of Kaskawulsh Glacier in Canada's Yukon Territory. Credit: Luke Copland/University of Ottawa

When Slims Lake drained in 2016, meltwater was redirected along a new channel. Credit: Luke Copland/University of Ottawa

ice is exposed than would be on a normal slope. Kaskawulsh Glacier is likely to retreat farther, and proglacial lakes will continue forming, Main said. That might drive more melting, although, she said, many reverse slope theories still need more data and modeling.

Kaskawulsh is retreating slower—22 meters (70 feet) annually—than other lake terminating glaciers in Alaska and the Yukon, Armstrong said. The median retreat rate, he explained, is 60 meters (200 feet) per year—almost 3 times faster. Kaskawulsh may therefore not be an extreme example of this lake-glacier feedback in the region. "There are many lake-terminating glaciers that are retreating much faster than Kaskawulsh, suggesting that their proglacial lakes could be more destabilizing," he said.

This research showed that we need to think of glaciers holistically and not as structures in isolation, Main said. "We have things all along the edges, and they're really difficult to include in studies," she said. "This study is just like one small example of trying to do that."

By **Danielle Beurteaux** (@daniellebeurt), Science Writer

Quaoar's Ring Defies Gravity

A small world in the outer solar system has a ring that shouldn't exist. According to new research, the ring material around the dwarf planet Quaoar is far enough away from the body that it should have coalesced into a moon but, for some reason, hasn't.

This gravity-defying ring could prompt astronomers to reexamine the physics of ring and moon formation and provide insight into the interactions between objects beyond Neptune. The researchers published their results in *Nature* (bit.ly/Quaoar-ring).

A Rule Breaker

The solar system beyond Neptune is home to several dwarf planets and numerous small icy objects left over from planet formation.

These objects interact gravitationally with each other, sometimes in violent collisions that create a cloud of debris that will often flatten into a disk.

Outside a theoretical boundary known as the Roche limit, that disk has the gravitational freedom to coalesce into a moon. Inside the Roche limit, however, gravity will shepherd the disk into a narrow ring, but the central body's tidal forces prevent the orbiting material from becoming a moon. The rings of Jupiter, Saturn, Uranus, Neptune, and several dwarf planets all follow this rule.

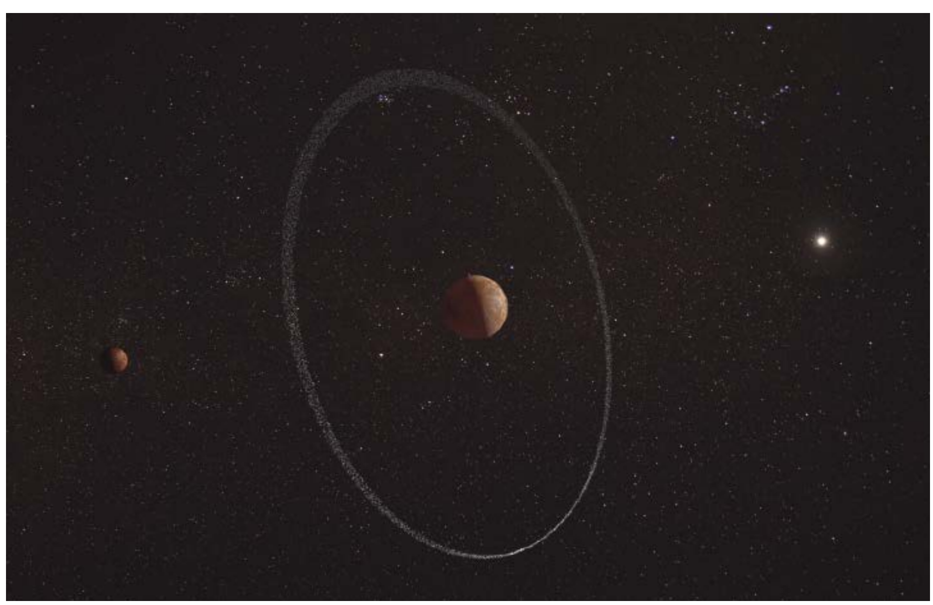
"Rings seem to be a natural outcome during the evolution of these bodies," said Bruno Sicardy, an astronomer at Sorbonne Université in Paris and a coauthor of the research.

"Rings seem to be a natural outcome during the evolution of these bodies."

Quaoar is a 1,110-kilometer-wide dwarf planet that orbits beyond Pluto in a region of the solar system called the Kuiper belt. Discovered in 2002, astronomers later found that it has a moon, Weywot, and likely has water ice on its surface from active ice volcanism.

Astronomers were trying to better map Quaoar's shape—it's not quite spherical—using the European Space Agency's (ESA) Characterising Exoplanet Satellite (CHEOPS). They were looking for stellar occultations, a phenomenon in which a nearby object of interest (Quaoar in this case) blocks distant background starlight.

Instead, they discovered that something also was blocking starlight on either side of the



Objects in the Quaoar system, illustrated here, are named for mythological figures from the Indigenous Tongva people of Southern California. Quaoar, the dwarf planet, is named for the creation deity, and Quaoar's moon, Weywot, is named for his son. Credit: ESA, CC BY-SA 3.0 IGO (bit.ly/ccbysa-igo-3-0) dwarf planet. Additional archival observations from 2018 to 2021 and computational models suggested that those occultations were likely from a thin circular ring of material 4,100 kilometers (2,500 miles) away from Quaoar.

Quaoar isn't the first dwarf planet to host rings, Sicardy said. "As there are thousands of such bodies beyond Neptune, we expected that rings should be commonplace in this region of the solar system." The rings of Chariklo, which started life in the Kuiper belt before Chariklo migrated inward toward Saturn, were discovered in 2013, and Haumea's rings were found in 2017. "And now, around Quaoar," he added.

If this ring is on its way to becoming a moon…then it's improbably lucky that the researchers spotted it.

The difference with Quaoar's ring, however, is that it lives far outside Quaoar's Roche limit, so it should have become a moon.

Too Coincidental

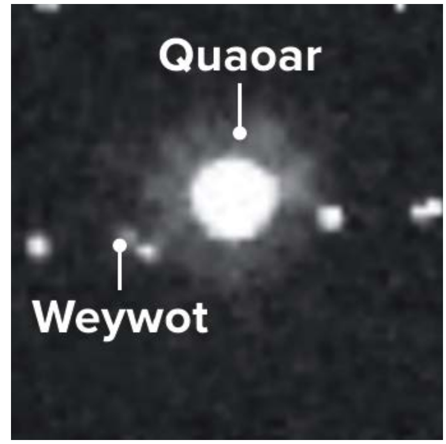
Michael Brown, an astronomer at the California Institute of Technology who helped discover Quaoar in 2002 but was not involved with this research, told the *New York Times*, "If the data weren't so convincing, I would insist they weren't real."

It's possible that Quaoar's ring might eventually form a moon, but it's not very likely. Because of Quaoar's weak tidal forces, such a ring outside the Roche limit should coalesce into a moon within a year or so of the debris field forming, Sicardy said. In the billions-of-years-long life span of Quaoar, that's less than a blink of an eye. If this ring is on its way to becoming a moon, as the Roche limit theory insists, then it's improbably lucky that the researchers spotted it, he explained.

Beyond the possibility of coincidence, the team had a few ideas that could explain the ring's survival beyond the Roche limit. It's possible that because we don't know Quaoar's shape very well, its Roche limit might be different than expected.

The team, however, believes that a stable gravitational resonance near the ring's orbit might prevent the ring particles from coalescing. Moreover, the ring's icy particles might be more elastic than expected, so they bounce off each other rather than sticking together to create ever larger clumps that eventually make a satellite. The Roche limit, the team concluded, is likely more complicated than previously thought.

The team plans to continue observing the Quaoar system using stellar occultations to better characterize the ring and see whether it evolves over time, Sicardy said. Quaoar, its ring, and its moon, Weywot, are small, dim, and far away, which makes them challenging to see with advanced ground- and space-based telescopes. "However," he added, "these images may reveal more extended rings and small satellites that will tell us more about Quaoar's—and other bodies'—environments."



This 2006 Hubble Space Telescope image of Quaoar and its moon, Weywot, is one of the clearest looks at the dwarf planet to date. Future observations with more advanced telescopes might sharpen the picture and reveal more objects in Quaoar's orbit. Other points of light in the image are background stars beyond the solar system. Credit: Hubble Space Telescope/Michael E. Brown, Public Domain

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Rivers in the Sky Are Hindering Winter Arctic Sea Ice Recovery

Arctic sea ice, shown here at its maximum extent in 2021, is declining in part because more atmospheric rivers are melting it. Credit: NASA Goddard Space Flight Center

Atmospheric rivers are reaching farther north with greater frequency than they were 4 decades ago, according to new research. These lofted highways of water vapor are dumping rain on recovering Arctic sea ice during the winter, when ice should be at its peak.

At any given time, multiple atmospheric rivers are moving more than a Mississippi River's worth of water from the equator to higher latitudes. When researchers first described the phenomenon several decades ago, it was seen as a midlatitude event, associated with flooding in California and snowmelt in the Pacific Northwest.

But recently, atmospheric rivers have been snaking their way to the poles as well. A new study definitively links these extreme weather events with broader trends in Arctic sea ice loss (bit.ly/Arctic-atmospheric-river).

Pengfei Zhang, an atmospheric scientist at Pennsylvania State University, began studying Arctic atmospheric rivers 2 years ago when he noticed an interesting trend. Whenever an atmospheric river stretched far enough north to reach the Arctic, sea ice immediately retreated. The effect was most pronounced in the dark months of winter, when Arctic sea ice was supposed to be recovering from summer losses to reach its maximum extent around late February or March.

"This means that the sea ice cover isn't able to extend to the maximum amount allowed by freezing temperatures," Zhang said.

Looking at satellite observations and meteorological data sets back to 1979, Zhang and his colleagues found that the number of atmospheric rivers that reached the Arctic had increased. At the same time, peak winter sea ice extent decreased.

Atmospheric rivers contribute to sea ice melting in a few key ways. The water vapor they contain traps more heat than dry polar air does, and this heat radiates down to the ice below. Heat is also released when water vapor forms rain or snow droplets. Finally, when rain reaches the surface, the warm droplets melt ice on contact.

The effect is pronounced enough that the ice's retreat can be seen on satellite imagery within a few days of an atmospheric river storm, as though a giant blow-dryer were aimed at the ice margin. When atmospheric rivers become more frequent, the number of setbacks per season increases too.

Using a combination of the historic satellite data and climate modeling, the team determined that about a third of recent sea ice decline in parts of the Arctic could be attributed to the dampening effect that increasingly common atmospheric rivers have on sea ice recovery. The impact was most pronounced in areas with the highest number of atmospheric rivers, including the Barents and Kara seas.

Because of the storms, when the Arctic warms in spring and summer, there is less sea ice to melt, and the dark ocean surface is exposed faster. These waters absorb more sunlight, which drives faster warming and even more melting.

The researchers used large-ensemble climate models, including LENS2 (Community Earth System Model 2 (CESM2) Large Ensemble Community Project), to determine how much the increase in atmospheric rivers could be attributed to climate change.

They found that 68% of the trend could be attributed to human-caused climate change, though natural climate variability like the Interdecadal Pacific Oscillation also played a role.

The work is "impressive," said Jonathan Wille, a polar meteorologist at ETH Zürich in Switzerland. "The authors of this study did an excellent job of quantifying the negative impacts of atmospheric rivers on early season sea ice growth."

Bracing for a Wetter, Warmer Arctic

A wetter and warmer Arctic will have far-reaching consequences. Increasingly frequent atmospheric rivers will make the Arctic a stormier place, with bigger waves that could further hinder ice formation. This more extreme environment could have a number of impacts on Arctic ecosystems. More sunlight hitting open ocean as a result of less sea ice, for instance, is already causing phytoplankton blooms to begin earlier and end later.

A wetter and warmer Arctic will have far-reaching consequences.

On a global scale, sea ice retreat could slow the ocean conveyor belt known as the Atlantic Meridional Overturning Circulation, which could lead to droughts or sea level rise thousands of kilometers from the Arctic.

"Unfortunately, there are many negative feedback loops related to sea ice melt, and this study highlights one of these processes," Wille said.

By **Rachel Fritts** (@rachel_fritts), Science Writer

Redefining "GLACIAL PACE"

As Earth's climate warms, glaciers and ice sheets are retreating, cracking, and adding to sea level rise at record speeds.

By Damond Benningfield

The lower part of Bear Glacier, Alaska, tripled in velocity in 2019, a phenomenon largely attributable to an ice-dammed lake suddenly draining through it. Credit: Lance King/Photodisc via Getty Images

When something is dragging along at an annoyingly slow rate, we often describe the pace as "glacial." Headlines have complained about the glacial pace of presidential appointments, college athletics reforms, and the early stages of the COVID-19 inoculation campaign. Online review sites carry snippy comments about glacially slow food deliveries and Internet service. In the movie *The Devil Wears Prada*, Meryl Streep's character tells a subordinate, "By all means, move at a glacial pace. You know how that thrills me." It was not a compliment.

It might be time to rethink that phrase. Glaciers and ice sheets are moving much faster now than they were just a couple of decades ago. The vast majority of them are retreating, thinning, cracking, or shrinking at unprecedented speeds.

"The most dominant reason we study the speed of ice is to understand the current and future contributions of ice to sea level rise."

Heated by Earth's warming atmosphere and oceans, Greenland's massive ice sheet is melting more rapidly and running into the sea. Weakened by changing currents in the Southern Ocean, the floating extensions of Antarctica's even bigger ice sheet are cracking off like slivers of peanut brittle. And smaller mountain glaciers from Alaska to New Zealand are vanishing, setting up potentially major consequences for people and ecosystems that depend on their water.

"Every region that has glaciers is out of balance," said Alex Gardner, a research scientist at NASA's Jet Propulsion Laboratory. "None are in equilibrium with the climate. None are healthy. And the problem has been accelerating."

All of that is contributing to one more speedup: the rise in global sea level. "The most dominant reason we study the speed of ice is to understand the current and future contributions of ice to sea level rise," said Richard Forster, a geologist and associate dean at the University of Utah.

"Ice velocity is a key parameter that provides critical information on the glacier response to climate change," said Romain Millan, a glaciologist at the National Centre for Space Studies in Grenoble, France. "Ice velocity observations are essential to better model the physics of glaciers and their evolution in the future."

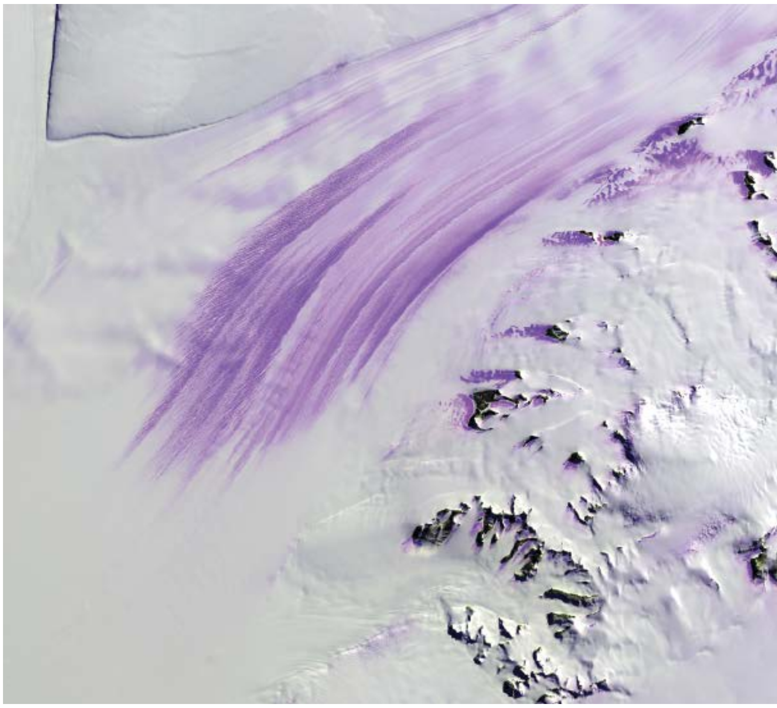
And researchers have said there is still a lot of uncertainty in their measurements and conclusions. "We're data starved," said Helen Fricker, a professor at the Scripps Institution of Oceanography at the University of California, San Diego. "We'll use anything we can get our hands on."

Multiple Tools for Measuring the Ice

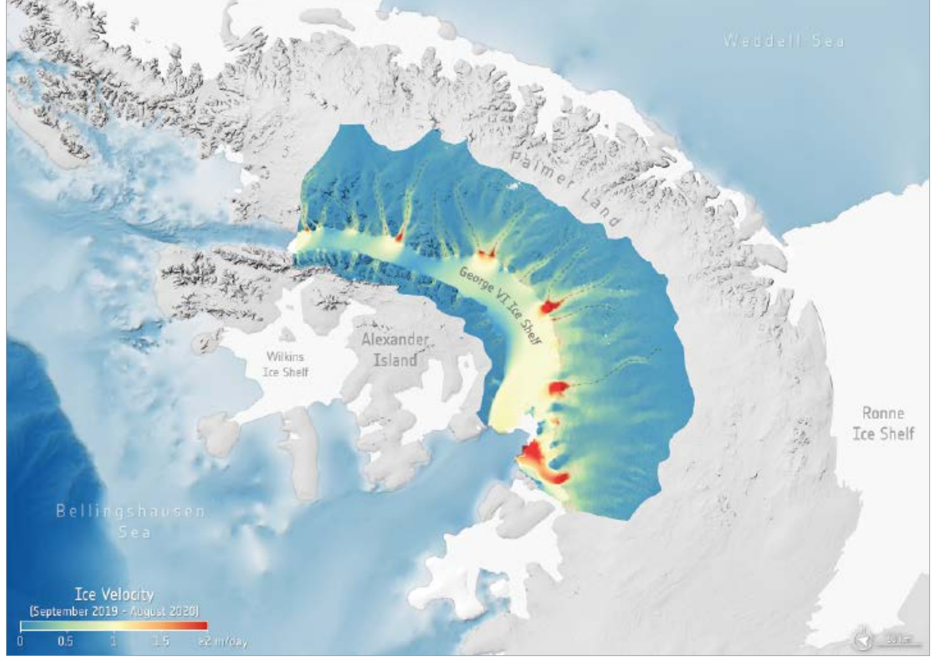
In the early days of tracking the speeds and directions of ice flows, observations made were entirely from the ground. "People would put a pole in the ground, come back later, see how far it had moved, then do it again," explained Richard Alley, a professor of geosciences at Pennsylvania State University. "To get the ice thickness, they'd stop, dig a hole, put in an explosive, set it off, and listen to the sound waves. But that only gave you information for one small point, and it was hard work."

Scientists still study ice from the surface, although today they use GPS to track motions and ground-penetrating radar to measure ice thickness and the contours of the bedrock. But they're also gathering data from the ground, air, and, especially, space.

"Thanks to the range of satellite approaches we have at our disposal today, we can now determine the sea level change contribution due to the polar ice sheets with a factor of 10 improvement in precision—roughly to within 0.1 millimeter of sea level change per year," said Andrew Shepherd, director of the Centre for Polar Observation and Modelling at the University of Leeds in the United Kingdom.



Slessor Glacier in Antarctica flows between mountains in this Landsat 8 image. The purple streaks, where winds have blown away the snow cover, indicate the flow direction. Credit: USGS



This map of part of the Antarctic Peninsula shows the velocity of ice in different regions of the George VI ice shelf. Credit: Contains modified Copernicus Sentinel data (2022), processed by ESA/Antarctic Ice Sheet Climate Change Initiative Programme

The approaches provide several major categories of observations.

Imagery is provided by the Landsat series of spacecraft, especially Landsat 8, which was launched in 2013 and passes over the same swath of Earth every 16 days, recording visible and infrared wavelengths with a resolution as high as 15 meters. “Landsat has produced some spectacular images, and it gives us a long historical perspective,” said Gardner, who is a member of several satellite mission teams. “It can observe how much the ice has receded, the change in area, and changes in flow.”

Altimetry comes from the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), which uses a laser to measure changes in elevation across all of Earth’s surface, with an emphasis on the ice sheets, where changes reveal how the ice is thinning. “For the glaciers in Greenland, altimetry shows that they can thin by as much as 10 to 20 meters a year,” said Eric Rignot, a professor of Earth system science at the University of California, Irvine. “In Antarctica, especially West Antarctica, the thinning is about 10 meters per year.”

The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO mission), which was launched in 2018, measures changes in ice sheet mass. Twin spacecraft maintain a laser link to precisely measure the distance between themselves. As they pass across Earth’s surface, tiny changes in the gravitational pull from the mass of the material below cause the gap distance to change. Precise calculations reveal the mass of the surface features, with repeated observations revealing how the mass has changed over time.

“It’s so sensitive that when we had the heavy rains here in California, GRACE told us that California got heavier—its gravitational pull increased as a result of all that water,” said Gardner. “The greatest changes in gravity are in the ice sheets and glaciers because all of that mass is being lost.”

A Game Changer at the Surface

Perhaps the most powerful arrow in the satellite quiver is the synthetic aperture radar (SAR) deployed by the European Space Agency’s Sentinel program—“a real game changer,” according to Shepherd, and “the ultimate technology,” according to Rignot.

Sentinel satellites emit pulses of radio energy at wavelengths similar to those produced by microwave ovens, then measure the return signals from the ice. SAR can operate in the dark and penetrate the clouds, providing almost continuous coverage.

Researchers don’t need to see specific landmarks, such as crevasses, to measure ice velocities. Instead, they apply a technique that allows them to measure pixel-to-pixel variations in intensity. They match surface patterns from image to image and track how the patterns have moved.

SAR also tracks phase shift, which describes the offset between two signals at different points of their cycles at a given time. “It’s orders of magnitude better at measuring glacial velocities—down to centimeter scales,” he said.

The next SAR-carrying mission is NISAR (NASA-ISRO Synthetic Aperture Radar), a joint project of NASA and the Indian Space Research Organisation, currently scheduled for launch in early 2024.

“NISAR is a whole ‘nother step up,” said Ian Joughin, leader of the mission’s cryosphere science team and a glaciologist at the University of Washington. It will operate at longer wavelengths, solving a problem created by certain changes in the surface.

In addition, NISAR’s radar will switch on for every pass over land, which isn’t the case for Sentinel. And whereas Sentinel and its predecessors have left big “donut holes” in observations near the South Pole, NISAR will provide more complete coverage of central portions of the continent. The combination of upgrades should allow the craft to accomplish in weeks what currently takes years, Joughin said.

“We’re data starved. We’ll use anything we can get our hands on.”

Ice Sheets Go on a Diet

Even with all of these advanced satellite observations, though, the mysteries of ice velocities are far from solved. “We can’t detect the full extent of the speedup with current technologies,” said Rignot.

Still, he and other scientists have taken stabs at it. They have estimated the amount of ice lost from the Antarctic and Greenland ice sheets and smaller glaciers, calculated the rate at which ice loss has accelerated, and figured the amount of water those losses have contributed to rising sea level.

In a 2022 paper in *Earth System Science Data*, for example, the authors calculated that combined, the Greenland and Antarctic ice sheets lost 7,563 gigatons of water (± 10%) from 1992 to 2020, raising sea level by roughly 21 millimeters [*Otosaka et al.*, 2022]. And the rate of mass loss rose from roughly 105 gigatons per year in the first 5 years of the study to 372 gigatons in the last 5 years—an increase of 280%. Greenland accounts for more than half of the total, even though Antarctica's ice sheet is more than 8 times more massive. (Antarctica holds enough ice to add 58 meters to global sea level, whereas Greenland banks only 7 meters.) In all, the two ice sheets have accounted for about one third of sea level rise, with the remainder coming from expansion of the warmer water and melting of smaller alpine glaciers.

A colorful DHC-3 Otter flies over mountain glaciers in Alaska in support of Operation IceBridge, a NASA project that surveyed glaciers across the globe, in 2014. Credit: NASA/Chris Larsen, University of Alaska Fairbanks

The bulk of mass loss on the Antarctic and Greenland ice sheets is driven by different processes, accounting for their different velocities: Whereas Antarctica is being chipped away along the edges, Greenland is melting.

Surface temperatures in Greenland have risen far more than the global average—roughly 5°C in winter and 2°C in summer. "Greenland is more temperate, so there's much more significant melt than in Antarctica," said Forster. "About half of its mass loss is coming from melting of ice versus discharge—icebergs breaking off. And the melting is increasing faster."

"The Greenland glaciers are retreating almost everywhere," said Rignot. "There are very few that aren't. They're moving at up to half a kilometer per year. And it's in all four corners."

The study of satellite observations concluded that from 1992 to 2020, Greenland's ice loss averaged about 277 gigatons per year.

The warmer climate melts enough ice in the summer to create lakes of up to a couple of kilometers across, Joughin said.

Some of the water escapes and flows all the way to the sea, but some of it tunnels through the ice and reaches bedrock. It then continues its downhill flow, serving as a lubricant for the ice above. "That changes the dynamics of the glacier," Fricker said. "It helps the ice slide faster over the bedrock, and that's increasing the ice flow rates."

"We're very interested in how glaciers slide," said Gardner. "There's a lot of progress in these sliding laws, especially over the last 5 years. We're establishing the relationship between water pressure at the bed of the glacier and how the glacier slides."

Researchers also need to understand the bedrock—its composition, slope, texture, and other characteristics—to accurately model how ice slides across it, with or without a lubricating layer of water. Airborne ground-penetrating radar provides some of that information. Missions are limited by weather, aircraft capabilities, and other constraints, so the models of solid rock below both the Greenland and Antarctic ice sheets remain incomplete.

Airborne missions also provide important looks at ocean conditions around ice sheets, which help scientists better understand how oceans contribute to ice loss and how the inflow of fresh water changes ocean temperatures, salinity, and circulation.

The combination of observations is helping scientists refine their models of how fast the ice moves, thins, and breaks away, improving forecasts of future mass loss and sea level rise.

Holy Bad Word, What Just Happened?

Three quarters of Antarctica is ringed by ice shelves—parts of the ice sheets, often hundreds of meters thick, that stretch out as floating extensions over the open ocean, fed by glaciers and ice streams that flow at anywhere from a few meters to a few kilometers per year. The ice shelves cover an area of more than 1.5 million square kilometers—as big as the entire Greenland Ice Sheet.

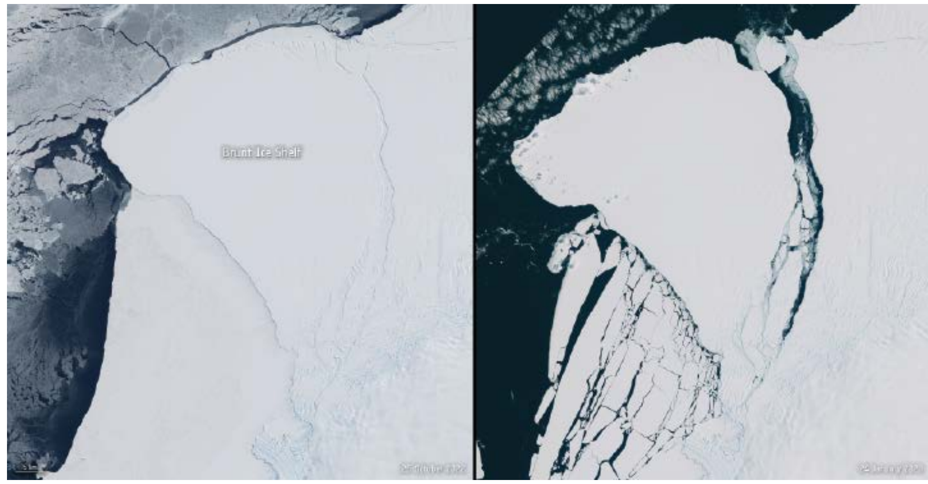
Most Antarctic ice shelves were stable for centuries. Over the past 2 or 3 decades, however, they've shown signs of weakening. They're moving faster as they lose more ice to calving hastened by warmer ocean currents below.

Greater instability among ice shelves is changing the continent's mass balance—the total mass determined by snowfall adding new ice to Antarctica, balanced by the loss of ice through calving and melting (the influence of melting is currently negligible in the still-cold continent). The total input has stayed about the same—roughly 2,000 cubic kilometers per year—but the output has increased significantly, chipping away at the total volume.

The problem is especially acute in West Antarctica, which faces the Pacific Ocean, and the Antarctic Peninsula, a tentacle-like spit that extends toward South America. Some ice shelves in these regions could collapse in the decades ahead, allowing glaciers behind them to push into the sea, adding to sea level rise.

Satellite observations show that glaciers in West Antarctica are advancing up to 100% faster today than they were in the 1980s, Rignot said, with some moving at up to 3 kilometers per year. A study led by Rignot reported “widespread glacier speedup that propagates 100 [kilometers] inland” to divides between major sections of the ice sheets [*Rignot e al.*, 2022].

The same study that measured global ice loss indicated that the loss in West Antarctica increased from about 39 gigatons per year in 1992–1996 to 131 gigatons per year in 2012–2016, with a drop to 94 gigatons in 2017–2020 thanks to a couple of seasons of especially heavy snowfall [*Otosaka et al.*, 2022]. In addition, altimetry showed that the thickness of the ice in West Antarctica is decreasing by as much as 10 meters per year, Rignot said. Changes in the region accounted for roughly 30% of all Antarctic ice loss.



A giant iceberg breaks away from the Brunt ice shelf in Antarctica in this pair of Sentinel images. The roughly 1,550-square-kilometer iceberg showed signs of cracking in October 2022 (left), then pulled away in January 2023. Credit: Contains modified Copernicus Sentinel data (2022–2023), processed by ESA, CC BY-SA 3.0 IGO (bit.ly/ccbysa-igo-3-0)

Changes in wind patterns are pushing warmer water toward the coast of West Antarctica, weakening ice shelves, especially where they intersect land at a glacier’s grounding line. The grounding lines of some shelves and glaciers are hundreds or thousands of meters below sea level, Rignot and other scientists explained, because the bedrock in some parts of West Antarctica forms a giant bowl that rests below sea level. If the ice shelf breaks off at the grounding line, the ice behind it can simply slide into the sea.

“It’s a matter of bottlenecks,” said Alley. “Almost all of the shelves are held back by friction with the sides, or by islands, or by local high spots on the seafloor. Because of that, they’re holding back the ice behind them. But if they weaken or go away, the grounded part can spread out and start floating, and that raises sea level.”

“Most of the time,” Alley said, “in most places, because the glaciers are wedged in by bottlenecks, changes tend to be moderate to slow. You see something that’s kinda sorta behaving itself. It sits there, sits there, sits there, doing little things, then suddenly, ‘Holy bad word—what just happened?’”

Perhaps the best-known example of this phenomenon was the 2002 collapse of the Larsen B ice shelf. It disintegrated in a matter of weeks, sending roughly 3,250 square kilometers of ice skittering into the ocean.

“That was a real wake-up moment for the whole community,” said Fricker. Landsat 7 observations indicated that the flow rates of adjoining glaciers into the gap increased by factors of 2–6 over the following few months, whereas ICESat data showed a drop of 38 meters in the elevation of one large glacier. (Larsen B was the most dramatic of several Larsen ice shelf losses. Larsen A broke off in 1995, and part of Larsen C followed in 2017. In all, Larsen has lost a quarter of its surface area.)

Scientists are concerned that the Larsen B scenario could also play out in West Antarctica with the Thwaites and Pine Island ice shelves as well as with a few smaller glaciers. All have their grounding lines deep below the surface, so if they perish, the bottlenecks holding back upstream ice would vanish.

Thwaites, in fact, has been dubbed “the Doomsday glacier,” although Joughin said the moniker is both misleading and unfortunate. “It’s likely to break up, potentially in the next decade, but...the ice won’t just come spilling out. It’s not like the ice shelf breaks and Florida suddenly floods,” he said.

Understanding the possible flow rates of Thwaites and other glaciers is complicated by uncertainties in the ice sliding law, the thickness of the ice, and the contours of the bedrock.

Researchers don’t need to see specific landmarks, such as crevasses, to measure ice velocities. Instead, they apply a technique that allows them to measure pixel-to-pixel variations in intensity.

“We’ve made great advances in our modeling over the last 20 years, maybe less,” said Gardner. “They’re quite complex models, and the sophistication required to run them is quite high. Now, we’re focusing on the edge conditions—the remaining unknowns.”

Drying Up the Rivers

The rest of the world’s glaciers are in trouble as well. Although they are little more than ice chips compared with the Greenland and Antarctic ice sheets, glaciers supply fresh water to roughly 2 billion people, so their disappearance would create hardships for surrounding populations and ecosystems.

Finger-shaped Himalayan glaciers in Bhutan end in blue lakes in this 2002 image. The lakes formed as the warming climate melted the lower reaches of the glaciers. Credit: USGS/NASA JPL/AGU

"The rest of the world is a big player now" in ice losses and contributions to global sea level rise, said Gardner.

A study of 98% of the world's glacier area, led by Millan and published last year in *Nature Geoscience*, found that many major systems are retreating at alarming rates [*Millan et al.*, 2022].

The study compared hundreds of thousands of pairs of images snapped by Landsat and Sentinel satellites at intervals of up to 400 days to plot changes in glacial coverage.

Glaciers in west Asia's Karakoram Mountains, for instance, retreated at roughly 2.3 kilometers per year over the study period, and Penguin Glacier in southern Patagonia retreated by 12 kilometers per year. The ice volume in three regions of the Andes Mountains, which provide water to some 4 million people in South America, was 20% less than reported in previous studies. And in the Upper Indus and Chenab basins, in the mountains of central Asia, glaciers lost about a tenth of a meter per year in equivalent meltwater—a potential problem for the 8 million inhabitants who depend on it.

Another study, led by David Rounce of Carnegie Mellon University and published in January in *Science*, projected that 26%–41% of the total volume of ice contained in glaciers outside the major ice sheets could vanish by 2100 if the atmosphere were to warm by 1.5°C–4°C, adding 90–154 millimeters to global sea level [*Rounce et al.*, 2023].

"Smaller [glaciers] are vanishing, and a significant number will be gone by the end of the century," Gardner said. "Unlike the ice sheets, those glaciers act as reservoirs or batteries for hydrologic systems. They store water during the cold, rainy months and release it during the dry, warm months. The implication is that the water flow will be reduced when it's most critical."

In addition, several large hydroelectric plants are planned for the high mountains of Asia. With reduced streamflow, the plants would provide less electricity and might even have to be scrapped.

Even the glaciers in the Rocky Mountains are feeling the effects. "They're very few and very small compared to other areas, but they're all retreating quite dramatically," said Forster. Glacier National Park in Montana, for example, draws tourists who expect to see…glaciers. As the park's nominal features retreat, however, there's less ice to serve as backgrounds for selfies.

And in the Wind River Range of Wyoming, the ecosystem depends on summer meltwater from the namesake glacier. As Wind River Glacier gets smaller and streamflow decreases, "it will disrupt the entire ecosystem," Forster noted.

Eventually, the contribution to global sea level from these smaller systems will taper off, leaving only the great ice sheets of Greenland and Antarctica to worry about. Scientists will continue to monitor the speed at which their ice melts, slides, breaks, and recedes.

We may see more glacial speed records in the decades ahead, although the magnitude of the jump from present speeds remains uncertain. "Ice retreat is already pretty fast, but if we can get a better handle on the climate, we can slow it down," said Rignot. "While retreat is inevitable, the speed can be controlled. That's the important point."

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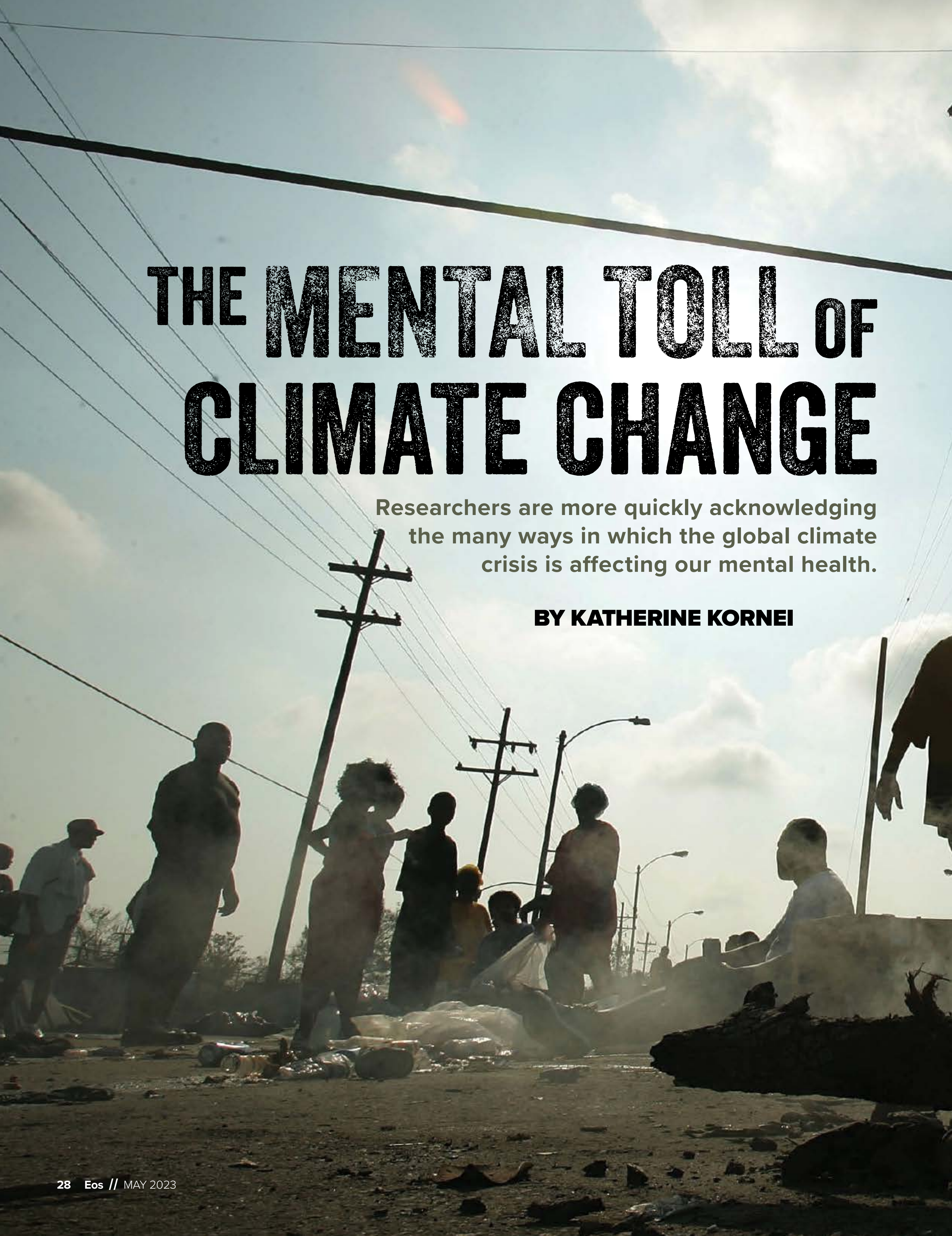

THE MENTAL TOLL OF CLIMATE CHANGE

Researchers are more quickly acknowledging the many ways in which the global climate crisis is affecting our mental health.

BY KATHERINE KORNEI

The increasing frequency and intensity of acute disasters are exposing more people to traumatizing events such as Hurricane Katrina, which devastated New Orleans communities and forced thousands of residents from their homes in 2005 Credit: Mario Tama via Getty Images

***Content warning:** This article discusses suicide and potential risk factors of suicide.*

Helping people navigate stress brought on by a relationship is standard practice for Megan Irving, a mental health therapist in Oregon. But, Irving and mental health professionals like her are seeing more clients suffering from a wholly different, and perhaps more pervasive, form of stress: unease brought on by the effects of our changing climate.

A growing body of research links the impacts of climate change to adverse mental health outcomes, such as depression, anxiety, post-traumatic stress disorder (PTSD), and substance abuse. But individuals and communities can take steps to bolster their emotional resilience to climate-related stressors, researchers have suggested.

Our physical health can suffer in many ways from the effects of climate change. The most obvious are cases of mortality. In July 2018, an unprecedented heat wave in Japan killed more than a thousand people; researchers later showed that the event could not have happened without climate change [*Imada et al.,* 2019]. And a myriad of nonlethal health issues is apt to worsen because of climate change. For example, respiratory problems have been linked to wildfires, which are increasing in severity and prevalence with climate change, a report concluded [*United Nations Environment Programme,* 2022].

But beyond the physical maladies brought on or exacerbated by climate change, there's the potential for a host of mental health issues, said Christie Manning, an environmental psychologist at Macalester College in Saint Paul, Minn. It makes sense that climate change would affect how we feel, said Manning, a coauthor of the "Mental Health and Our Changing Climate" report published by the American Psychological Association, Climate for Health, and EcoAmerica (bit.ly/mental-health-climate-change). Its deleterious effects seem to dominate the news, and the issue often seems so intractable and beyond our control, she said. "The individual things we can do feel so incommensurate with the problem."

The Trauma of Sudden-Onset Events

When it comes to evaluating how our mental functioning is affected by climate change, Manning and other mental health experts have tended to find consistent patterns. "It's pretty standard these days to think about the mental health impacts in three broad categories," said Manning.

The first category is brought on by acute events such as devastating storms, wildfires, and floods. Sudden-onset events can cause trauma, which often manifests as PTSD and has been linked to anxiety, major depressive disorder, and substance abuse, said Manning. In 2006, researchers surveyed more than 400 community college students living in the region around New Orleans. All of the study participants had been affected by Hurricane Katrina the year prior, and more than half of them lived in the Ninth Ward, an area that suffered some of the worst destruction from the storm. The researchers found that nearly half met the diagnostic criteria for PTSD [*Lowe, et al.*, 2013].

After a slew of destructive wildfires plagued California in October 2017, residents living in affected counties reported feelings of trauma and guilt, in addition to anxiety, depression, and solastalgia (defined as melancholia related to a home environment that has been altered) according to a survey of more than 2,200 households. And that distress persisted over time, the research team found; survey participants reported similar feelings both immediately after the fires and several months later. "We need people to understand that this is not 'over' for us," one respondent wrote. The researchers, led by Mitchell Snyder at the University of California, Davis, reported their results at AGU's Fall Meeting 2022 (bit.ly/AGU22-wildfire-survivers).

"PEOPLE ARE STILL ANXIOUS AND DEPRESSED AND ANGRY ABOUT WHAT THEY'RE SEEING PLAY OUT."

Natural disasters, including floods and hurricanes, have also been linked to increased suicide rates. Jennifer Horney, an epidemiologist at the University of Delaware in Newark, and her colleagues showed that in U.S. counties that experienced a natural disaster, suicide rates increased by 23% in the first 3 years after the disaster compared with the 3 years preceding the disaster [*Horney*, 2020]. The team reported its results in 2020 in the journal *Crisis*.

As the climate continues to change, the frequency and intensity of acute events such as wildfires and hurricanes are predicted to increase. Compound disasters—multiple destructive events, such as a mudslide following a fire—are also more likely with climate change, recent research has shown. "Climate change is growing in its physical manifestations," said Manning. And that means that more people will be exposed to potentially traumatic events, she said. "It's getting harder and harder not to experience climate change."

Chronic Conditions

Events that evolve more slowly—and are almost chronic in nature—are responsible for the second category of impacts. Gradual shifts in our environment linked to climate change include prolonged droughts, desertification, and persistent heat waves. Changes in temperature and weather patterns can trigger a sense of uncertainty, said Manning. "It makes people question what's happening." Particularly for people who live close to the land—whose identities, cultures, or livelihoods depend on environmental predictability—that uncertainty can escalate to feelings of hopelessness and despair, sometimes with tragic results.

Azar Abadi, a climate epidemiologist at the School of Public Health at the University of Alabama at Birmingham, and her colleagues recently studied the association between drought exposure and risk of suicide in the United States. They found that drought conditions, as estimated using 2000–2018 data from NOAA's Evaporative Demand Drought Index, were correlated with higher rates of firearm suicide, particularly among nonurban populations. "We found that rural communities are more susceptible," said Abadi, who shared her team's findings at AGU's Fall Meeting 2022 (bit.ly/AGU22-drought-suicide). These findings are particularly concerning, said Abadi, because some groups of rural dwellers are already overrepresented in suicide cases compared with the general population.

Researchers have also predicted that the suicide rate in the United States will

Credit: iStockphoto/VladTeodor

increase overall as temperatures rise. A team led by Anna Belova, an economist at the consulting firm ICF, considered different global climate models and scenarios corresponding to 1°C–6°C of warming. They showed that up to roughly 1,600 additional suicides could occur each year because of climate change [*Belova et al.*, 2022]. The researchers reported their results in *GeoHealth*.

Suicide is a tragic manifestation of mental anguish, and it's important to understand its causes, said Abadi. However, she noted, climate change and mental health are controversial issues, and it can be difficult to engage people in those discussions. "When these two topics are combined, it's not an easy conversation." But it's critical to acknowledge mental distress, said Abadi. "When we talk about well-being, it's a combination of physical health and mental health."

Climate Anxiety

The third broad category of climate change–induced mental health impacts is often characterized as lingering and unshakable concern, worry, or anger. Those feelings—sometimes referred to collectively as climate anxiety—are brought on by an awareness that the environment is, perhaps indelibly, changing. And a person doesn't need to have experienced trauma personally to be affected, said Manning. Instead, the concern, worry, or anger can be "connected to a worry about what is going to happen and what we've lost already," she said.

Of the three categories of climate change–related mental health impacts, climate anxiety most commonly afflicts Irving's clients. That's perhaps because people are more cognizant of climate change and its deleterious effects than they were even a decade ago, said Irving, who sees clients in Portland and Rockaway Beach, Ore. Climate anxiety appears to be pervasive: A poll conducted in 2019 on behalf of the American Psychological Association revealed that more than two thirds of Americans suffer from it [*American Psychological Association*, 2020].

Worry and uncertainty are natural responses to a growing awareness of climate change, even if a person's cultural identity or livelihood isn't intimately tied to the environment, said Irving. "People are still anxious and depressed and angry about what they're seeing play out."

Angry, Baffled, and Horrified

The responses of younger generations to climate change are often marked by a sense of outrage, Irving said: "Young folks are angry and baffled and horrified that more action isn't being taken." Emotions such as anger, shame, grief, and despair are often evident in youth-led protests about climate change. Many youth feel that they're being forced to grow up in a world where the effects of climate change have already been set in motion by previous generations: A recent survey of 10,000 people aged 16–25 (that is, individuals largely belonging to Generation Z) revealed that more than 80% believe people have failed to take care of the planet [*Hickman et al.*, 2021].

Irving's generation predates Generation Z, but thinking about climate change and its effects triggered similar emotions for her, she said. And those feelings in turn started to affect how Irving functioned. "I started feeling anxious," she said. "I started getting depressed."

Roughly a decade ago, Irving began looking for resources to support her own mental well-being. Taking care of oneself—"doing the work," Irving called it—is particularly important for people working on the front

Residents fill sand bags as they prepare for the arrival of Hurricane Florence in September 2018 in Wrightsville Beach, N.C. Credit: Mark Wilson via Getty Images

lines of mental health: It's those individuals who are often expected to be strong for others and provide solutions.

While searching for resources to help her process her own climate change–related feelings, Irving discovered the Climate Psychology Alliance, an organization devoted to supporting people experiencing distress resulting from climate change. Irving has since participated in several of the alliance's climate cafés, which are virtual gatherings open to anyone worried about the climate crisis. The events are facilitated but largely function as open forums for participants to discuss their concerns and meet like-minded people.

Realizing that other people were wrestling with similar feelings was cathartic, said Irving. "I found some relief in knowing that I wasn't the only one that was feeling this way."

When Homelands Change

The mental health impacts of the climate crisis do not afflict everyone, nor do they strike in the same way when they do. Researchers have found that communities living close to the land in places where environmental conditions are changing particularly rapidly are often at the highest risk.

One person who knows that well is Ashlee Cunsolo, a health geographer at the Labrador Campus of Memorial University of Newfoundland in Canada. Cunsolo has worked with Inuit communities for more than a decade and has documented the "ecological grief"—a term she coined with colleague Neville Ellis [*Cunsolo and Ellis*, 2018]—felt by community members as their homelands change.

Seasonal cycles in Nunatsiavut, a self-governing territory of Inuit in Labrador, are largely dictated by the ebb and flow of sea ice. A thick layer of ice means safe conditions for traveling and hunting, but Labrador, like many parts of the Arctic, is warming. It's one of the fastest warming places in Canada, said Cunsolo. "Labrador has been at the front lines of the changing climate for decades." As a result of that warming, sea ice is forming later in the year and retreating earlier than it used to; it's also not growing as thick now as it once did. These days, there are longer stretches of time when it's not safe to venture out onto the ice.

The feeling of being cooped up weighs on Inuit mental health, Susan Saksagiak, a resident of Nain, the largest community in Nunatsiavut, told Cunsolo. "When people have to stay home longer and longer, it's hard on the mind."

In 2013, Cunsolo conducted interviews with Saksagiak and 23 other Inuit individuals for *Lament for the Land*, a documentary film she created in partnership with the five Inuit communities of Nunatsiavut (lamentfortheland.ca/). Again and again, community members shared with Cunsolo their feelings of losing their sense of identity, which in turn negatively affected their mental well-being, as their homeland changed before their eyes. "You lose control of a part of your life," Derrick Pottle, a resident of Rigolet, the southernmost community in Nunatsiavut, told Cunsolo.

But several years ago, community members came together to fight against the losses they were experiencing: They started developing programs designed to improve the mental health of their youth and bolster their community's overall resilience. The work was initially motivated by tragedy: In 1 year, seven Nain youth died by suicide. Beyond providing a supportive environment for Inuit youth, community members also sought more opportunities to engage in meaningful cultural connections and cross-generational dialogue.

One of the programs that resulted, Going Off, Growing Strong, engaged Inuit youth in activities like preparing traditional foods, fixing snowmobiles, and doing arts and crafts with elders.

"All of these things make people feel connected to their culture and their ancestors and their family and their community," said Cunsolo. A sense of connectedness—that is, social support—has been linked to lower levels of psychological distress, research has shown [*Banks and Weems*, 2014].

"We need community," said Irving. "When you have something as scary as climate change, one of the best ways to cope is to find community."

"WHEN YOU HAVE SOMETHING AS SCARY AS CLIMATE CHANGE, ONE OF THE BEST WAYS TO COPE IS TO FIND COMMUNITY."

The programs developed by people in Nunatsiavut are an example of the positive outcomes of something Cunsolo terms "gritty hope." Sometimes hope in its barest incarnation can be an excuse for inaction, said Cunsolo, but that's not the case with gritty hope. "It's hope that stems from pain and mobilizes action." Gritty hope is having a mindset of not dwelling on what's been lost already and being prepared to stave off future losses, said Cunsolo. "We can fight like hell to make sure more isn't lost."

Cunsolo engages in her own form of gritty hope. It's what keeps her going, she said, when her work forces her to watch people suffer as their ancestral lands and ways of life irrevocably change. "It's like you're surrounded by the pain of the world all the time," she said. "It's a heavy burden to carry." Cunsolo advocates for policies that recognize the human, mental, and emotional impacts of climate change. Getting the word out about how climate change affects us in so many different ways and connecting with people give her purpose, she said.

Taking Time for Self-Care

Mental self-care in the face of climate change looks different for different people.

Josh Edelson, a freelance photojournalist based in Novato, Calif., regularly photographs wildfires in the Golden State. He can be embedded with a blaze for days at a time, living out of his car and dodging falling trees that are still burning on the inside, all the while shooting images for the Associated Press and the *Los Angeles Times*, among other news organizations.

Over the roughly 10 years he's been documenting wildfires, he's seen them change. "Fires have become bigger and more intense," said Edelson.

And ever since the 2015 Valley Fire destroyed Middletown, a small town in Northern California near Santa Rosa, blazes have been more likely to tear through inhabited areas, he's noticed. "Almost every single year thereafter [there] has been a bigger fire with more damage and more destruction." Those conflagrations leave wakes of destruction of both structures and life, which Edelson has witnessed firsthand.

After Edelson emerges from covering a blaze, it can take several days for him to feel normal again, he said. Sometimes even everyday events like grocery shopping with his wife can trigger fire flashbacks. "We go to the store, and I'm looking around imagining what things would look like on fire," he said. "It still echoes in your mind."

Edelson said he finds it helpful to process his experiences with other people who understand what he's been through. "I have a core group of other photographers that cover fires," he said. "We talk with each other a lot, and that's incredibly therapeutic."

Seeking support from others is a time-tested way of combating mental health issues, including those triggered by climate change. It's therapeutic to be understood and validated, and communities can take on a variety of forms ranging from individuals bonded by a shared experience to strangers brought together by a support group. Irving often encourages her clients to seek out people who can relate to their experiences. "I have a growing list of support groups," she said.

Beyond increasing social cohesion, people can boost their resilience to distress brought on by climate change in other ways. One technique is to develop a practice—otherwise known as a habit or a routine—that gives you strength, said Manning. That might be mediation or mindfulness or involvement in a faith-based community. Or it could be therapy, she added. The Climate Psychology Alliance maintains a directory of more than 100 mental health providers across the United States, Canada, and the United Kingdom who are committed to addressing mental health needs related to climate change (bit.ly/climate-therapists).

Individuals can also help themselves and others by learning and practicing the tenets of psychological first aid. This interventionist strategy—designed to help people feel safe, calm, empowered, connected, and hopeful in the aftermath of a disaster—can help reduce the incidence of long-term mental health problems, research has shown [*Birkhead and Vermeulen,* 2018].

Preparing for the future can furthermore help individuals cope with climate change–related stress, said Manning. Reconfiguring a home to make it more weather and disaster resistant—raising it up on stilts to stave off flooding, for example—can be beneficial to mental health, she said.

But even relatively simple (and less expensive) steps help, too. Putting together a box of emergency supplies stocked with food and first aid items can make people feel more prepared and better able to face an uncertain future, said Manning. "People who do this kind of preparation work feel better and fare better."

Engaging in positive work that makes a difference is another proven method for bolstering climate change–related resilience: When people help others, their own well-being increases. That's been shown time and time again, in communities ranging from individuals affected by hurricanes [*Spialek et al.*, 2019] to people affected by flooding [*Woodhall Melnik and Grogan,* 2019].

Climate change is altering our lives in fundamental ways, and it's daunting to think about the environmental and societal shifts that will transpire. But emotional resilience to the effects of climate change can be honed, albeit with dedication and effort.

Perhaps conversations around health—both physical and mental—might be a key to helping people honestly face climate change, said Abadi. "I noticed that when we talk about health, people actually listen," she said. "Health is the best communication pathway about climate change."

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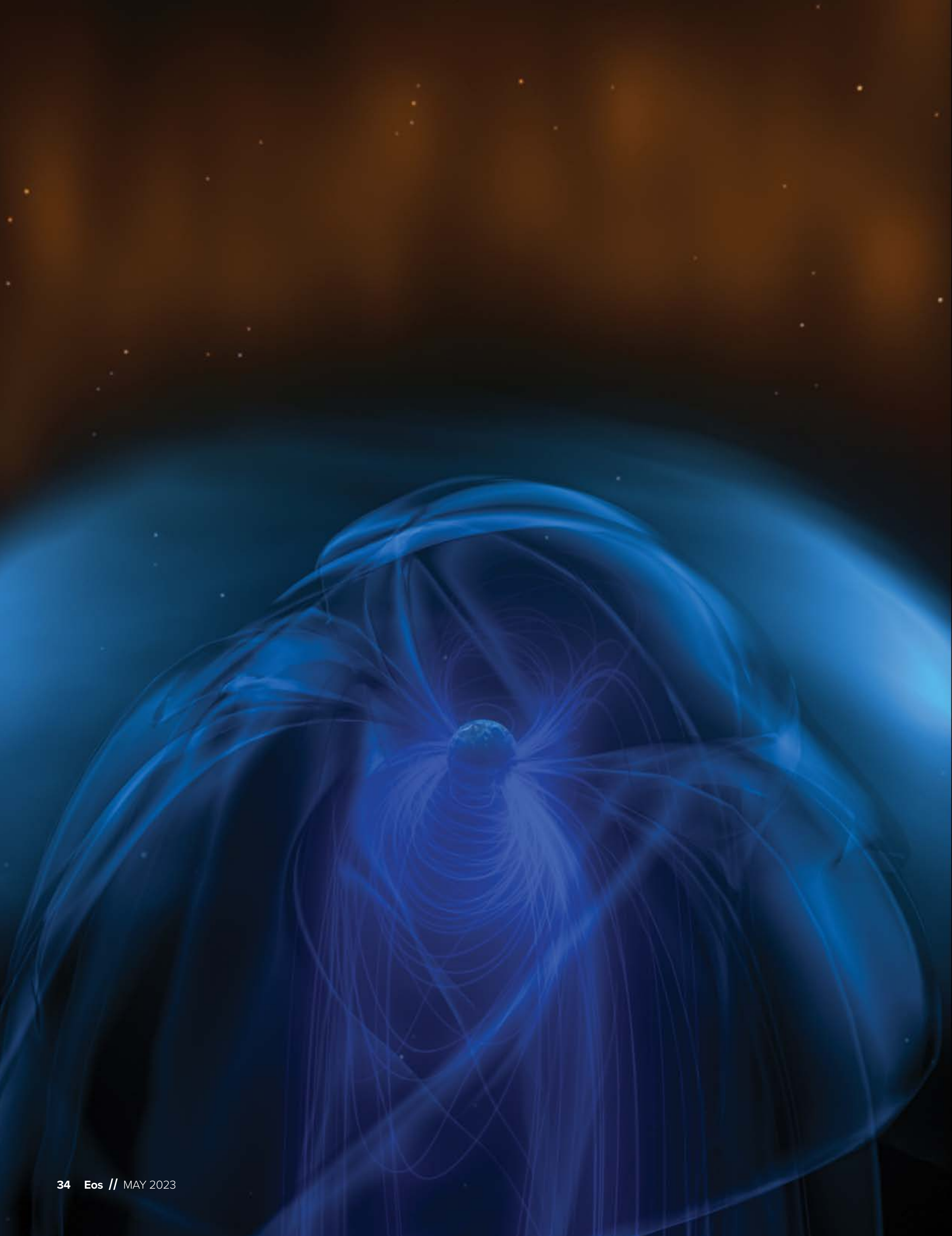
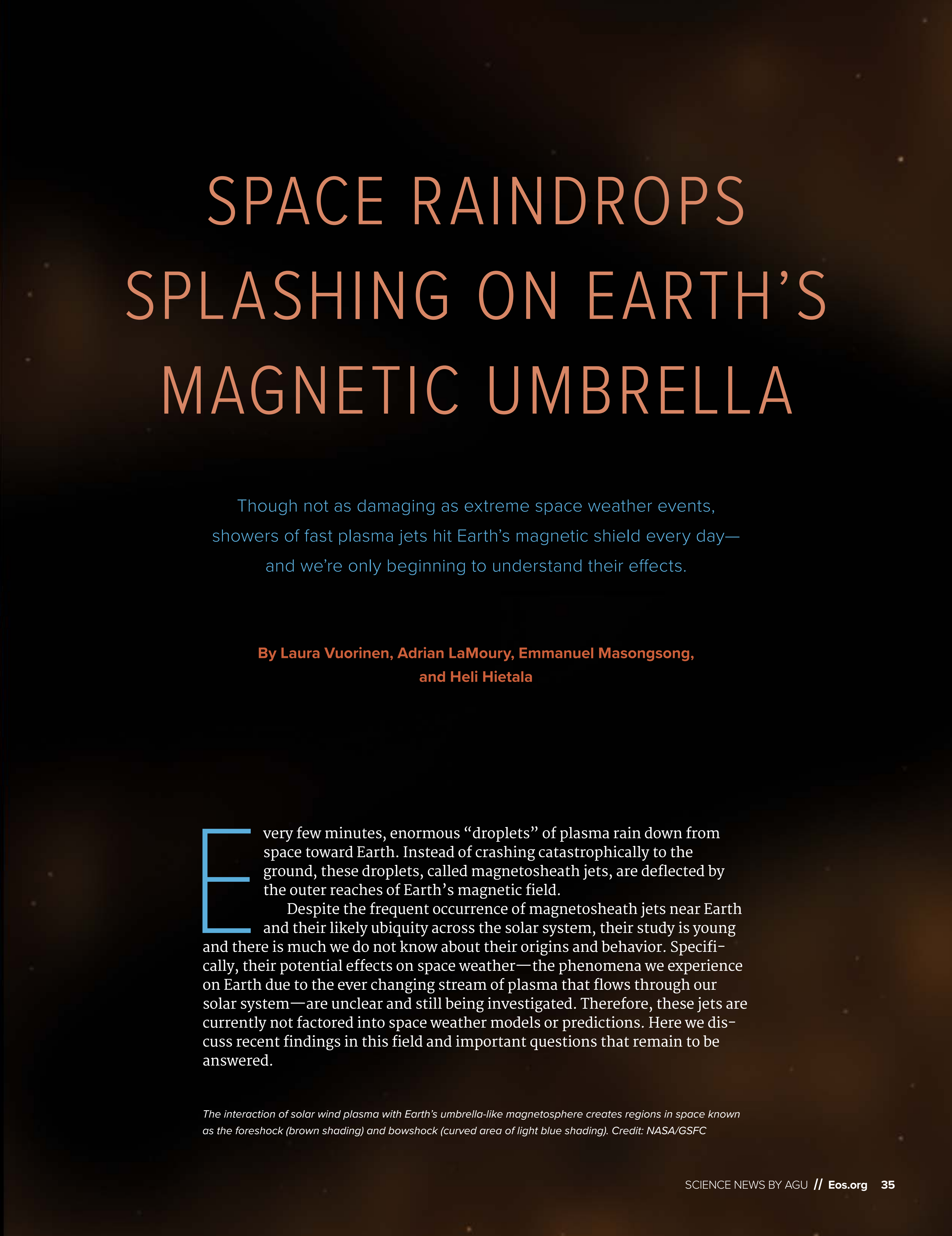




SPACE RAINDROPS SPLASHING ON EARTH'S MAGNETIC UMBRELLA

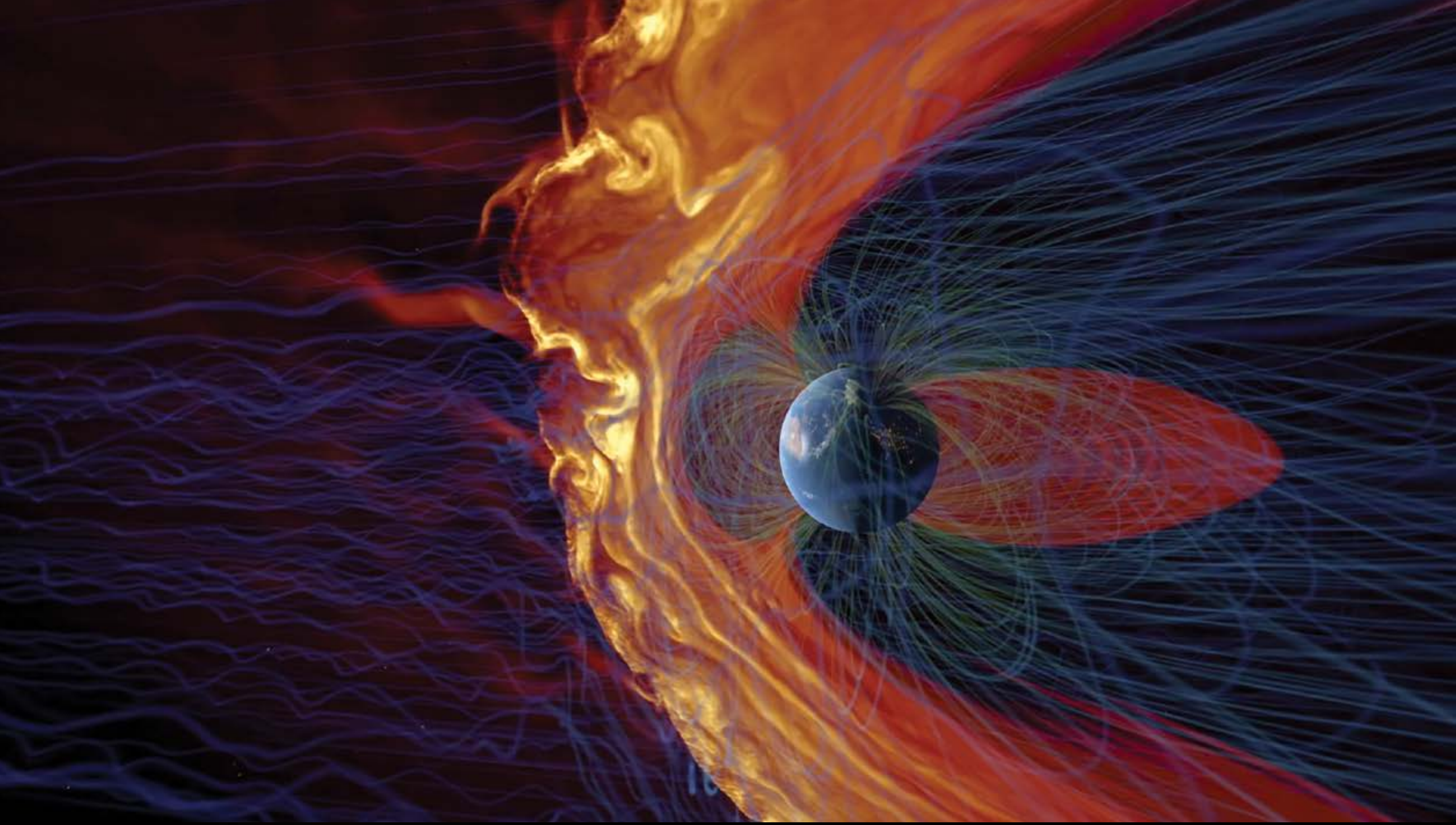
Though not as damaging as extreme space weather events, showers of fast plasma jets hit Earth's magnetic shield every day—and we're only beginning to understand their effects.

By Laura Vuorinen, Adrian LaMoury, Emmanuel Masongsong, and Heli Hietala

Every few minutes, enormous "droplets" of plasma rain down from space toward Earth. Instead of crashing catastrophically to the ground, these droplets, called magnetosheath jets, are deflected by the outer reaches of Earth's magnetic field.

Despite the frequent occurrence of magnetosheath jets near Earth and their likely ubiquity across the solar system, their study is young and there is much we do not know about their origins and behavior. Specifically, their potential effects on space weather—the phenomena we experience on Earth due to the ever changing stream of plasma that flows through our solar system—are unclear and still being investigated. Therefore, these jets are currently not factored into space weather models or predictions. Here we discuss recent findings in this field and important questions that remain to be answered.

The interaction of solar wind plasma with Earth's umbrella-like magnetosphere creates regions in space known as the foreshock (brown shading) and bowshock (curved area of light blue shading). Credit: NASA/GSFC



Solar wind plasma interacts with Earth's magnetic field in this computer-generated visualization. Credit: Advanced Visualization Lab, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign (National Science Foundation award 1445176)

Earth's Umbrella

We live under a protective umbrella, or bubble, called the magnetosphere (Figure 1). This is the region where Earth's magnetic field shields us from the solar wind—the constant stream of plasma that flows from the Sun. The solar wind drags the Sun's magnetic field far into interplanetary space, where it clashes with other objects in the solar system. Were it not for Earth's own magnetic field, the solar wind would strip away our atmosphere, leaving our planet a barren rock like Mars.

The solar wind blows at hundreds of kilometers per second (~1 million miles per hour), squashing Earth's magnetosphere on the side nearest the Sun and dragging it out like a wind sock on the other side. The surface over which the competing pressures of the solar wind and the magnetosphere are balanced—the surface of the bubble, in other words—is called the magnetopause. The solar wind is highly variable, with its speed and magnetic field orientation constantly changing, and as the wind ebbs and flows, this surface compresses and expands to maintain the balance without bursting the bubble.

The solar wind is supersonic, and analogous to what happens when an airplane flies at supersonic speeds through the atmosphere, a shock wave—called the bow shock—forms outside the magnetosphere on the Sun-facing side. At this shock front, solar wind plasma is slowed, heated, and compressed, creating a turbulent layer known as the magnetosheath, and it is here that we find fast plasma jets.

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Space Weather Big and Small

We experience space weather because of our planet's interaction with the solar wind. Large and dramatic space weather events, such as explosive solar flares and coronal mass ejections, can have potentially catastrophic effects on modern civilization.

The famed Carrington event of 1859, the strongest coronal mass ejection ever observed, produced auroras as far south as Mexico and Cuba, with many people reporting the night sky to be as bright as day. The massive compression of the magnetosphere during the event caused severe and widespread damage to telegraph systems, resulting in the electrocution of operators and outbreaks of fires.

If such an event were to happen today, the disruption to our technology and infrastructure would be profound, with costs estimated to be in the trillions of dollars. From GPS failure to widespread electrical power outages, a Carrington-sized coronal mass ejection could bring the world to a standstill. It's hard to imagine a world where telephone and Internet communications are suddenly cut off, let alone one without power to charge devices.

Fortunately, events of this intensity are very infrequent compared with a human lifespan. They are among the least common natural disasters—the superhurricanes or giant earthquakes of the space weather world. Yet we experience less extreme forms of space weather every day, exemplified by the dazzling auroras at high northern and southern latitudes, which are consequences of solar wind interacting with our magnetosphere.

Forecasting occasional major hurricanes is crucial for public safety and survival, but on a regular basis, most people are more interested in whether their local forecast calls for rain. Similarly, while space weather scientists urgently look to forecast major events, we are also constantly monitoring the more mundane types of space weather activity and their fundamental effects. This is important both in space, to protect satellites and astronauts who are vulnerable to energetic particles, and on Earth, where the induced currents from magnetic field disturbances can cause gradual degradation in power transformer stations and other infrastructure, such as pipelines and rail lines.

From GPS failure to widespread electrical power outages, a Carrington-sized coronal mass ejection could bring the world to a standstill.

Magnetosheath Jets: Space Rain

Magnetosheath jets rain on Earth's magnetosphere every day [*Plaschke et al.*, 2018]. As the solar wind is processed, slowed down, and compressed at the bow shock, jets can sporadically emerge, influenced by the structure of the shock itself.

The global-scale geometry of the bow shock is important. The bow shock's curvature and the orientation of the interplanetary magnetic field carried by the solar wind determine the structure of the shock and how it processes the solar wind. Zooming in, spacecraft observations and model simulations show us that shock regions where the interplanetary magnetic field is perpendicular to the shock surface look completely different from regions where the magnetic field is almost aligned with the shock surface (Figure 1).

In regions where the magnetic field is perpendicular to the shock surface, the shock transition is extended and the shock surface is corrugated, as opposed to the more abrupt transition and simpler structure where the magnetic field and the shock surface are more closely aligned.

The explanation for this difference is rooted in geometry. At shock regions where the solar wind magnetic field is perpendicular to the shock, solar wind particles can reflect off the shock and travel far back away from Earth along incident magnetic field lines. These reflected particles collectively form a turbulent region—the foreshock—because of their interaction with the incoming solar wind. The adjacent shock region is also affected, becoming corrugated and rippled.

When the solar wind flows through such a ripple at the shock, it is not slowed as much as the surrounding solar wind is. Thus, fast magnetosheath jets can emerge when the solar wind flows through a rippled shock. In addition, plasma structures from the turbulent foreshock can cross the shock, emerging as jets. Because the formation of jets is linked to the foreshock, jets are most often observed when the solar wind magnetic field lines are pointed directly from Earth to the Sun, known as radial interplanetary magnetic field conditions. During these conditions, the foreshock is present at the nose of Earth's bow shock.

Once jets have formed, they travel through the magnetosheath toward Earth, plowing through the surrounding slower plasma with dynamic pressure comparable to the upstream solar wind. Some jets dissipate along the way, but many of them survive the journey across the whole magnetosheath and eventually collide with high

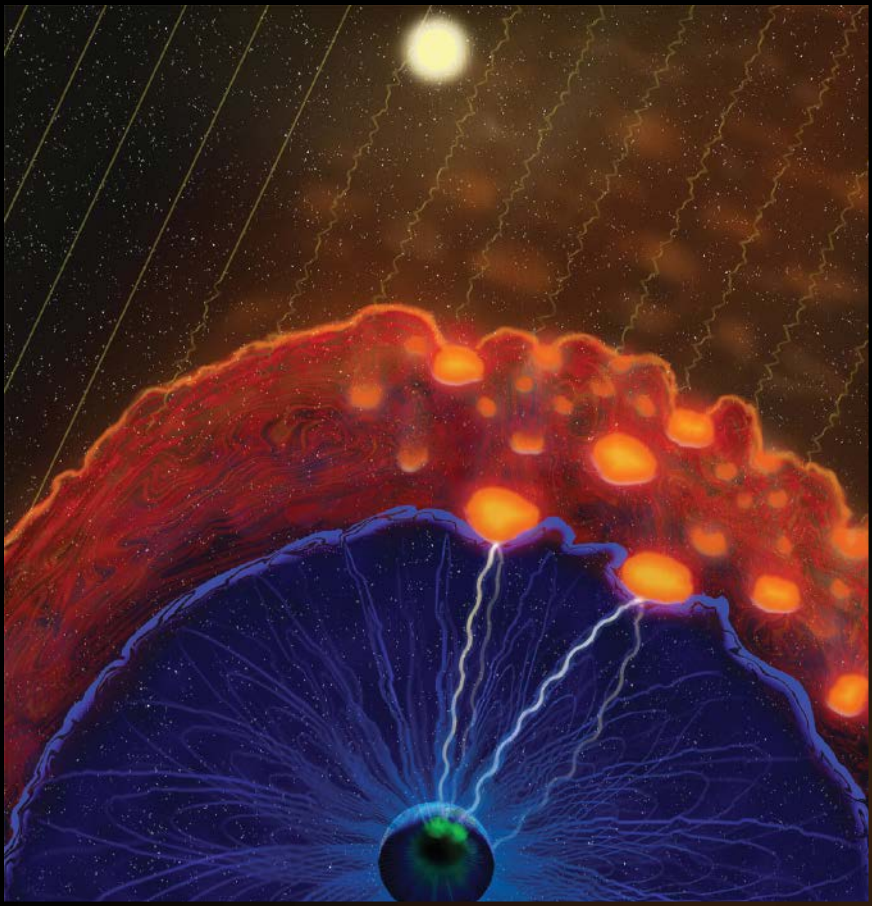

Fig. 1. The solar wind with its interplanetary magnetic field (yellow lines) flows from the Sun and forms a shock wave called the bow shock (bright orange line) where it meets Earth's magnetic field upstream of the planet. At the bow shock, the solar wind is slowed, except for fast plasma jets (orange globules) emerging from where the shock wave is corrugated, adjacent to the turbulent foreshock region (brown shading at top right). Jets travel through the magnetosheath (red swirls), and eventually, some of them hit the magnetopause (bright blue line), the outer edge of Earth's magnetosphere (blue shading). Earth's magnetic field (faint blue lines) and an aurora in Earth's ionosphere are also represented. Credit: E. Masongsong, H. Hietala, L. Vuorinen, A. LaMoury

momentum into the boundary of Earth's magnetosphere, the magnetopause (Figure 2).

These collisions may indent the magnetopause, perturbing the outer edge of the magnetosphere and setting in motion a chain of events spanning from the magnetosphere all the way to the ionosphere. The magnetopause surface can rebound, for example, vibrating like the skin of a drum and launching plasma waves into the magnetosphere. Jet impacts also have been linked to observations of the aurora. To forecast the potential space weather effects of jets, we must understand the conditions under which they occur and when they will hit the magnetopause at the highest rates.

When It Rains, It Pours

Our knowledge of magnetosheath jets relies on data captured by spacecraft surveying the near-Earth electromagnetic environment. Launched in 2007 and still going strong, NASA's THEMIS-ARTEMIS five-satellite mission in particular has greatly enhanced our understanding of many areas of space and space weather, from the solar wind and its interactions with Earth's magnetic field to the aurora and even plasmas around the Moon.

In a recent study using THEMIS data, researchers observed that the frequency of jets reaching the magnetopause is highly dependent on the properties of the solar wind at the bow shock [*LaMoury et al.*, 2021]. They found that when the solar wind's magnetic field is nearly radial, jets are expected to hit the magnetopause every few minutes—that is, more than 17 times more often than when the solar wind's magnetic field reaches Earth at an oblique angle. They also found that more jets arose during intervals of "fast" solar wind (which travels about twice the normal velocity). These intervals vary with the 11-year solar cycle, so the number of jets hitting the magnetopause may exhibit the same periodic dependence.

In addition to controlling the structure of different bow shock regions, the orientation of the solar wind magnetic field influences what happens at the magnetopause. Zooming in on this boundary where the solar wind magnetic field meets Earth's magnetic field, we see that geometry comes into play once again.

Namely, if the solar wind magnetic field is oriented southward, opposite to Earth's northward magnetic field, erosion of the magnetopause can occur via a process known as magnetic reconnection (Figure 2). Reconnection is a key process in plasma physics, in which the connectedness of magnetic field lines is fundamentally changed and energy stored in the magnetic field is explosively released.

In the case of the magnetopause, antiparallel field lines of the solar wind connect with those of Earth, peeling them away from the Sun-facing side of the magnetosphere. This has the effect of weakening Earth's magnetic shield, allowing solar wind plasma and energy to enter Earth's magnetosphere. Thus, one of the most critical aspects of forecasting space weather is monitoring the solar wind magnetic field orientation far upstream of Earth.

Although measuring the north–south component of the solar wind magnetic field before it arrives at Earth (together with solar wind speed and density) can help us prepare for space weather storms, it does not give us the full picture of how space weather evolves at Earth. Much more frequent rain showers (i.e., jets) may play a role that, until recently, was not considered to control magnetic reconnection, sparking debate in the magnetospheric physics community. Jets, because of their high dynamic pressure, have been observed compressing the magnetopause boundary, which helps initiate reconnection, as opposite magnetic fields are being pushed together more efficiently [*Hietala et al.*, 2018].

In addition, researchers have suggested that the magnetic field orientation in jets may be different from field orientations in the surrounding magnetosheath. *Nykyri et al.* [2019] observed jets with

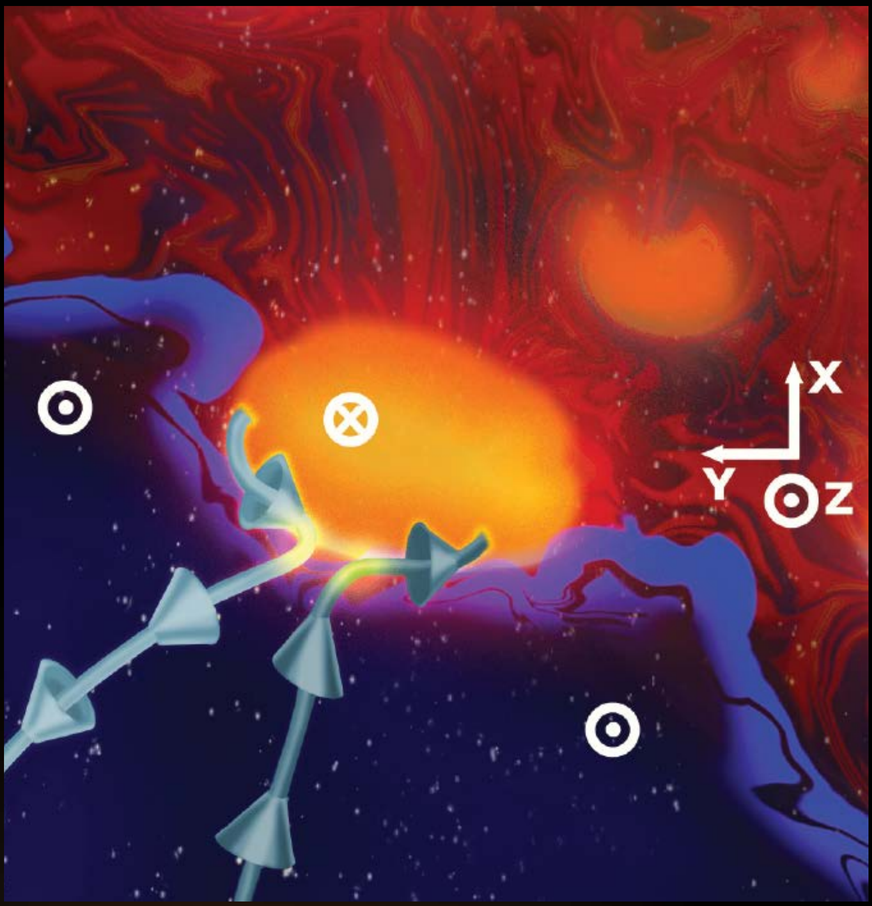

Fig. 2. Antiparallel magnetic field lines can merge during magnetic reconnection, which transforms magnetic energy into the kinetic energy of particles. At Earth's magnetopause (bright blue), this can happen when Earth's northward-oriented (⊙) magnetic field (gray curve with conical arrows) meets a plasma jet (orange globule) with southward-oriented (⊗) magnetic field. Credit: E. Masongsong, H. Hietala, L. Vuorinen, A. LaMoury, F. Beyene

southward magnetic fields propagating toward the magnetopause and triggering reconnection despite measurements at the time showing that the solar wind magnetic field was oriented northward. This was likely not an isolated occurrence, and it caused a chain of events leading to increased geomagnetic activity on the nightside of the magnetosphere, opposite from the Sun.

Vuorinen et al. [2021] performed a statistical study of the north–south component in jets versus the surrounding magnetosheath using THEMIS data, further confirming that jets often carry southward magnetic fields even when the solar wind magnetic field is northward. The combination of jets compressing and introducing southward fields to the magnetopause may be favorable for triggering reconnection, even during solar wind conditions when we are not typically expecting it. This result highlights the importance of studying the magnetosphere's behavior during times of a radial interplanetary magnetic field.

By studying jets in near-Earth space, we are potentially learning about processes taking place around other planets like Venus and Jupiter, as well as at huge astrophysical shocks such as those arising from supernovas.

Ongoing Efforts and Unanswered Questions

Thus far, we have considered jets only in Earth's magnetosheath. However, it is very likely that jets arising from rippled shock surfaces exist elsewhere in the solar system and beyond. Therefore, by studying jets in near-Earth space, we are potentially learning about processes taking place around other planets like Venus and Jupiter, as well as at shocks driven by coronal mass ejections or even at huge astrophysical shocks such as those arising from supernovas.

Many aspects of jets are still debated. In addition to their formation at ripples in shock surfaces, other formation mechanisms have been proposed. *Raptis et al.* [2022], for example, provided evidence that pockets of fast solar wind trapped downstream of the shock can become jets as the shock surface is regenerated at a new position, in a natural cycle of shock reformation. It is not entirely clear how different mechanisms may relate to the inherent properties of jets seen in the magnetosheath. In particular, the behavior of the magnetosphere during times of radial interplanetary magnetic field is not as well studied as the extreme cases of strong southward or northward field. As our understanding of jets increases, we expect that they will come to be considered a fundamental part of Earth's complex magnetospheric system.

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A Deeper Dive into Wintry, Carbon-Absorbing Antarctic Waters

Every year as the austral winter sets in, frigid Antarctic air blasts the Southern Ocean. The chill dissipates the warmth of the ocean's surface water, and cold, dense layers form in the sea's upper reaches. Known as Subantarctic Mode Water (SAMW), the cold water body amasses north of the Antarctic Circumpolar Current before sliding north into the ocean interior.

SAMW is an essential component of the global climate system: It is critical to our understanding of climate change. As the ocean's global conveyor belt assimilates the wintry water mass, the well-mixed water is transported into the Pacific and Indian oceans, bringing nutrients, oxygen, and carbon—lots and lots of carbon. The Southern Ocean takes up 50% of the carbon absorbed by the world's oceans, and models and observations show that SAMW has accumulated 20% of the ocean's anthropogenic carbon inventory and more than half of its anthropogenic heat uptake.

In a new study, *Bushinsky and Cerovečki* characterize SAMW using novel data collected by the Biogeochemical Argo (BGC-Argo) float array. By characterizing the water mass's role in nutrient export and carbon uptake, scientists can better interpret ocean measurements and models.

The array's floating robots measure oxygen, nitrate, and pH up to 2,000 meters below the sea surface. Over 7 years, the researchers observed SAMW across its entire wintertime formation area.

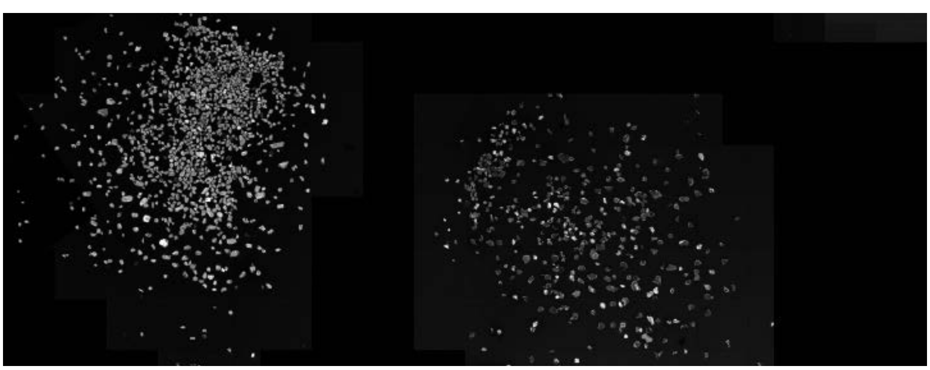
The authors found that SAMW that forms in the Pacific Ocean sector is colder, fresher, and higher in oxygen, nitrate, and dissolved inorganic carbon than its Indian Ocean sector counterpart. The Pacific SAMW also displayed a seesaw pattern of variability across the years, which linked to the Southern Annual Mode and the El Niño–Southern Oscillation the dominant climate modes of variability in this region.

In both Pacific and Indian SAMW, the biogeochemical properties depend on the density of the newly formed water. In addition, when SAMW initially forms, it is undersaturated in oxygen. The authors say this is related to cooling and entrainment of deep water depleted with oxygen opposing the injection of oxygen from the atmosphere.

Last, the results show that the partial pressure of carbon dioxide was near or above atmospheric levels during SAMW formation. This revelation suggests that SAMW formation does not directly drive ocean uptake of present-day carbon dioxide; however, it may still be an overall sink of anthropogenic carbon.

SAMW plays a critical role in global climate and carbon systems. The authors note that this improved understanding of its formation and fundamental properties will have ramifications for subsurface ocean models, interpretations of ocean measurements, and, ultimately, global climate and biogeochemical models. (*AGU Advances,* https://doi.org/10.1029/2022AV000722, 2023) **—Aaron Sidder,** *Science Writer*

Prospecting for Copper with Machine Learning and Zircons



Zircons vary in shape, size, and texture, as seen in this scanning electron microscope cathodoluminescence image Credit: Chetan Nathwani

Zircons are common, hardy minerals that can be found in rocks upwards of 4 billion years old. Their structure and texture can reflect the conditions in which they formed, earning them a reputation as nature's time capsules. And according to new research, with the power of machine learning, scientists can use zircon textures to identify valuable mineral deposits.

In a new study, *Nathwani et al.* developed a method to distinguish minute differences between zircon grains formed in copper-associated rocks and those formed in granitic rocks. Their method could help scientists search for mineral deposits and probe the origins of different sediments.

The researchers used a machine learning tool called a convolutional neural network (CNN), which specializes in image analysis. Using samples collected in southern Peru, a region that produces much of the world's copper, they found that the CNN could identify shapes and textures unique to zircons found near copper deposits. The model could also distinguish these copper-associated zircons from those found in other kinds of rock in the region with an 85% success rate.

Copper has broad industrial applications, from electronics to construction, and the study suggests that pairing machine learning with more traditional techniques could make it easier to explore and identify copper deposits. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2022JB025933, 2023) **—Rachel Fritts,** *Science Writer*

Scientists Can Now Map Lightning in 3D

In a new study, scientists developed a new way to map lightning in 3D, both inside and outside a cloud. Credit: Mathias Krumbholz/Wikimedia, CC-BY-SA 3.0 (bit.ly/ccbysa3-0)

Studying lightning is as hard as you might expect.

One promising technique to study the ephemeral surges is to measure radio waves generated by a lightning event using an array of antennas. This technique, called radio-frequency interferometry, has been around since the late 20th century. In prior work, for example, researchers integrated this method with polarized antennas to pinpoint the angular position of a strike and to detect the polarization state of the incoming radio waves.

Still, this method can localize a lightning strike and detect its polarization in only two dimensions. This limitation prevents scientists from answering fundamental questions, such as where and how lightning starts in a cloud and how quickly different discharge processes occur.

In a new study, *Shao et al.* extended radio-frequency interferometry and polarization detection to three dimensions. Adding a third dimension could resolve these long-standing problems in lightning physics.

Their second-generation BIMAP-3D (Broadband Interferometric Mapping and Polarization in 3D) system uses two observation stations. These stations, which are separated by 11.5 kilometers, each consist of four sets of broadband and polarized antennas arranged in a Y shape. By using both stations simultaneously, scientists can map lightning and detect polarization in three dimensions.

The authors describe two techniques for triangulating the path of a lightning strike by combining data from the two stations: one based on geometry and the other on time of arrival. They can integrate these two analyses for accurate triangulation.

Under favorable conditions, the researchers could pinpoint a lightning strike's source location to within several meters at an altitude of kilometers aboveground. What's more, they could track the development of lightning within fractions of a microsecond.

The team then applied their new instrumentation and analysis techniques to several observed lightning strikes. They computed 3D maps showing the shape and development of each lightning event, including both cloud-to-cloud and cloud-to-ground events. They even demonstrated that for events with linear polarization, BIMAP-3D can deduce the orientation of the radio polarization in three dimensions.

These novel capabilities, the authors say, expand the horizon of what's possible in the study of lightning physics. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2022JD037955, 2023)

—Morgan Rehnberg, *Science Writer*

To Estimate Plant Water Use, Consider the Xylem

Plants are an integral part of the water cycle. Certain plant traits, like rooting depth and water storage, can govern water availability across an entire ecosystem.

Quantifying these traits can help scientists predict the mortality risk of trees facing droughts and the effects of forest composition on local hydrology. Yet many of them remain difficult to measure or estimate with current methods.

In a new study, *Li et al.* demonstrate that stable isotopes (^2H, ^{18}O) in a tree's water-transporting xylem provide reliable estimates of several plant traits related to water use. Rather than assuming generic values for diverse forests, the scientists discovered that these traits can be estimated from isotope data that are commonly collected and widely available.

The researchers measured the isotopic makeup of hydrogen and oxygen in xylem water from 30 eastern hemlock trees at the University of Connecticut over 7 months across a range of riparian topographic positions. They incorporated these data, along with meteorological and groundwater data, into a model that predicted various plant traits.

Researchers sampled 30 eastern hemlock trees in Connecticut, focusing on stable isotopes in tree xylems. They used these observations to calibrate their hydrologic models of the region. Credit: Nicholas_T/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

They found that the model's predictions for root depth, plant water storage, evapotranspiration, and evaporation in soils were correlated with the diameter of the hemlock tree and its location on a slope. The ability to estimate these plant traits accurately using relatively basic xylem measurements could help scientists solve water resources challenges now and in the future as the climate changes, the authors say. (*Journal of Advances in Modeling Earth Systems (JAMES)*, https://doi.org/10.1029/2022MS003263, 2023) **—Sarah Derouin,** *Science Writer*

Quantifying Greenhouse Gases Emitted by Tropical Soils

Nitrogen changes form as it cycles between air, soil, and living organisms. Soils, for example, emit nitrogen either as inert dinitrogen (N_2), which dominates our atmosphere, or as nitric oxide (NO) or nitrous oxide (N_2O), the greenhouse gases that warm it.

Understanding what types of nitrogen gas emissions are coming from soils is important in managing greenhouse gas emissions and characterizing nitrogen budgets globally. But because Earth's atmosphere is teeming with dinitrogen gas, it can be difficult to measure the small N_2 emissions from soils amid the high background concentrations.

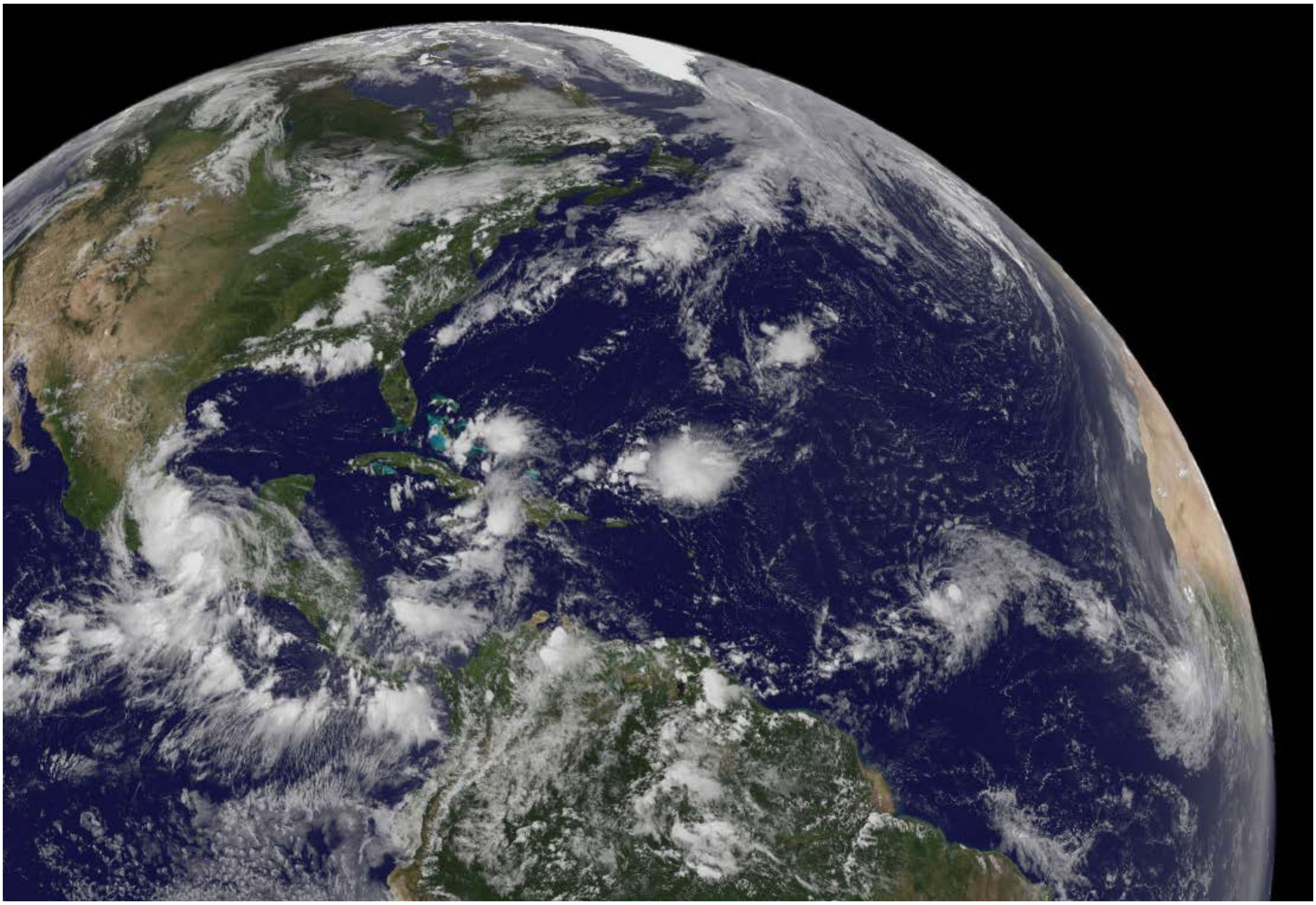
Almaraz et al. headed to Puerto Rico to better understand how tropical soils emit nitrogen as N_2 or N_2O. They discovered that dinitrogen dominated soil emissions, but the exact ratio depended on the topography and soil moisture.

The researchers took soil cores from Luquillo Experimental Forest in Puerto Rico at various topographic gradients, including valleys and ridges and the slopes that lie in between. In the laboratory, they incubated the samples in an artificial atmosphere, which replaced the soil's nitrogen with mixtures of oxygen and helium. This method allowed the team to measure the forms of nitrogen as they left the soil.

They found that dinitrogen was more prevalent than other forms. Furthermore, wet valleys emitted more N_2, NO, and N_2O than aerated ridges and slopes. The team estimates that in total, tropical forest soils emit about 37 kilograms of nitrogen per hectare per year, with 99% of the gas being N_2.

The researchers suggest that dinitrogen fluxes might have been underestimated in lowland tropical forest landscapes in the past, and they call for a reevaluation of nitrogen budgets in light of these new findings. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2022JG007210, 2023) **—Sarah Derouin,** *Science Writer*

Linking African Winds to Atlantic Storms



A series of tropical storms stretching from the west coast of Africa to the Caribbean is visible in this image taken by NOAA's GOES 13 satellite in August 2012. New research helps clarify how Atlantic tropical cyclones are affected by atmospheric patterns known as African easterly waves. Credit: NASA Goddard Space Flight Center/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Previous research has indicated that African easterly waves are associated with up to 80% of major Atlantic hurricanes on shorter timescales. However, it is unclear exactly how the waves influence the formation of tropical cyclones on seasonal and longer timescales.

New research by *Danso et al.* helps to clarify this relationship, suggesting that African easterly waves contribute to the intensity, timing, and location of the formation of tropical cyclones but do not affect the number of cyclones that form in a given season.

The researchers conducted high-resolution simulations of these waves and storms using a computational weather forecasting framework known as the Weather Research and Forecasting (WRF) model. The simulations covered the atmosphere from the Gulf of Mexico to the coast of northern Africa—the major region where tropical cyclones develop—and lasted from August through October of 2020, coinciding with peak tropical cyclone season. In the simulations, the researchers either retained or removed African easterly waves to help isolate their role in tropical cyclone formation.

In line with other recent research, the team found that subtracting African easterly waves from the simulations did not change the number of cyclones that formed. However, with the waves removed, simulated storms that formed were more intense and the peak period of their formation shifted from September to August. In addition, more cyclones formed in the Gulf of Mexico, and fewer formed off the coast of northern Africa.

The findings suggest that African easterly waves influence the large-scale atmospheric environment in which Atlantic tropical cyclones form. On their own, however, the waves are not reliable predictors of future changes in the frequency of these storms, the authors say, adding that other mechanisms generate these storms when the waves are not present. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL100590, 2022) **—Sarah Stanley,** *Science Writer*

How Thick Is Antarctic Ice, and What Is Underneath?

An aircraft tows the electromagnetic induction bird (visible at the center) over fast ice in McMurdo Sound, Ross Sea, Antarctica. Credit: Greg Leonard, University of Otago

Ice at the edge of the Antarctic continent hosts a flourishing ecosystem. Seals and penguins breed, fish mature, and algae thrive, all thanks to sea ice tethered to the shore, called fast ice. To understand how fast ice protects this ecosystem and to assess the area's health and future, scientists need to gauge how thick shore-bound ice is along the different parts of the coast—an estimate that has eluded scientists in the past.

In a new study, *Langhorne et al.* provide more reliable estimates of Antarctic fast ice thickness by measuring it from an airplane using a method called airborne electromagnetic induction sounding. This technique is an improvement on previous efforts. For example, it has a wider geographic range than drilling into the ice; unlike radar, it can penetrate sea ice; and it provides more certain estimates than satellites.

The sounding method uses a device called a bird towed beneath the aircraft at an altitude of just 15 meters. The bird transmits a magnetic field through the ice and into the conductive seawater. There, the magnetic field induces tiny electric currents that the bird can detect to tell the scientists how thick the ice is.

The researchers used the system to survey a 700-kilometer-long section of coast in the Ross Sea, a huge embayment in the Southern Ocean that is home to the Scott Base, McMurdo, and Zucchelli research stations. The area is known for its floating glaciers and ice shelves, both of which are stabilized by fast ice.

During the survey in November 2017, fast ice in the region was about 3 meters thick on average, with the most common thickness being 2 meters. About half of the surveyed ice was rough—the result of being pummeled against the shore by storms. Meltwater from beneath ice shelves and floating glaciers formed a slushy layer of ice crystals up to 10 meters thick below some of the fast ice.

The measurements provide a baseline for future studies, the authors say. With this information, they hope to track Antarctic fast ice as Earth changes and the climate warms. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2022JC019459, 2023)

—Saima May Sidik, *Science Writer*

A New Measure of Roughness Could Advance Earthquake Geophysics

When two rock surfaces interact with each other in a fault zone, their roughness influences the outcome, including when earthquakes occur. Still, the underlying mechanics of this relationship remain unclear.

In a recent study, *Beeler* presents a new, alternative metric for analyzing surface roughness that could inform how roughness influences fault dynamics.

Scientists have traditionally measured surface roughness using the average height of the bumps on a surface and that surface's length. However, this means that the roughness of the same rock will vary depending on the length being considered; according to this metric, surfaces are rougher at small scales and smoother at large scales.

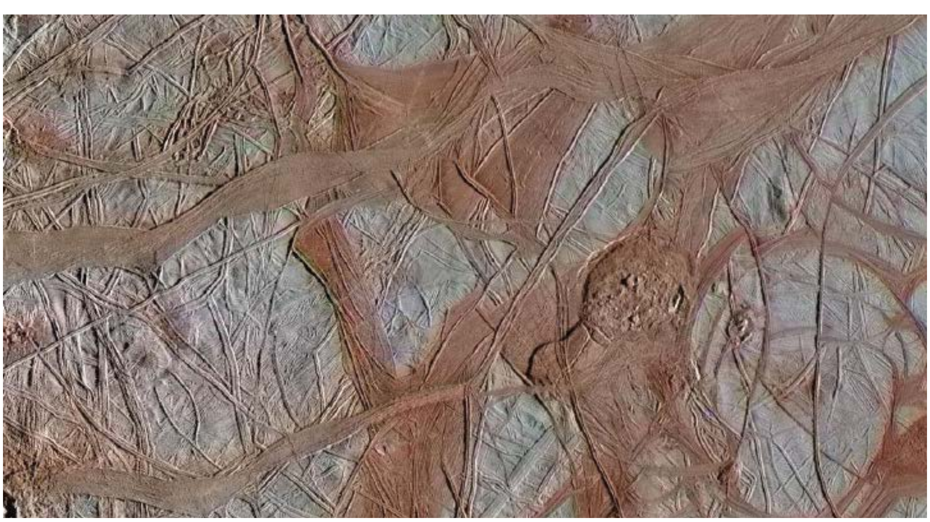
By contrast, instead of averaging height over surface length, the new metric averages height over wavelength, or the distance between the repeating, larger-scale ups and downs of a rough surface, within which finer-scale bumps and troughs may occur. Using wavelength in this calculation yields a measure of roughness that no longer varies with the scale being considered.

Compared with the traditional length-based metric, the new wavelength-based metric is simpler and more applicable over a wide range of scales. But according to the author, use of the scale independent metric could show that roughness plays a much smaller role in earthquakes than previously thought. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2022JB024856, 2023) **—Sarah Stanley,** *Science Writer*

Europa's Plate Tectonic Activity Is Unlike Earth's

Plate tectonics represents a defining framework of modern geoscience, accounting for large-scale features on Earth's surface, such as mountains and valleys, as well as the processes that shape them, like volcanoes and earthquakes. Present-day plate tectonics has not been observed on any other world in the solar system, and evidence of past activity on planets such as Mars and Venus is circumstantial. Perhaps the best case for extraterrestrial plate tectonics is found in the floating ice shell of Jupiter's moon Europa.

Collins et al. provide the most comprehensive look yet at possible plate tectonic activity on Europa. They extended prior work to include more surface regions and a more sophisticated geometric approach, basing their analysis on a global map of Europa derived from images captured by NASA's Galileo orbiter.



A complex pattern of ridges and bands named Arachne Linea is seen in this enhanced-color image of Europa's surface taken by the Galileo spacecraft on 26 September 1998. New research shows that this landscape was formed by the jostling of nearby tectonic plates. Credit: NASA/JPL-Caltech/SETI Institute

Team members identified prospective tectonic plates as regions of contiguous geography bounded by surface discontinuities. After identifying these boundaries, they inferred a time sequence of activity at the boundaries based on which discontinuities appear to lie atop or crosscut adjacent features. Once this sequence of events was established, they worked backward from the most recent event to reconstruct the likely motions of each plate needed to bring it into alignment with its neighbors.

The researchers applied this approach to three regions of Europa that they deemed most promising to have hosted past tectonic activity. They found that to best reconstruct the motion of the surface, large areas suspected to be plates in previous studies had to be broken into smaller subplates along less obvious boundaries. This observation helps explain why some prior studies found that large plates did not reconstruct well or behaved in other unexpected ways, the researchers note.

The authors draw four broad conclusions about plate tectonic activity on Europa: It is spatially widespread; it is regionally confined rather than globally connected; it occurs intermittently and is not happening now; and during past activity, plates drifted limited distances of 10–100 kilometers.

Each of these traits distinguishes tectonic activity on Europa from that on Earth. The driving mechanisms for Europa's plate tectonic system are surely also different. To further reveal these mechanisms and to answer other questions about Europa, planetary scientists need more high-resolution observations, the researchers say, which the upcoming JUICE (Jupiter Icy Moons Explorer) and Europa Clipper missions may provide. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2022JE007492, 2022) **—Morgan Rehnberg,** *Science Writer*

University at Buffalo

ASSOCIATE OR FULL PROFESSOR IN GEOLOGICAL OR CLIMATE HAZARDS

The Department of Geology at University at Buffalo (UB), The State University of New York, invites candidates to apply for the position of **Professor of Empire Innovation**, at the rank of **Associate Professor** or **Full Professor**. The selected candidate will receive support through the SUNY Empire Innovation Program (EIP), which recognizes exceptional scholars with a proven track record of externally funded research and offers a generous compensation and start-up package.

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The Professor of Empire Innovation will teach courses at the graduate and undergraduate levels, mentor graduate students, and maintain an active externally funded research program which will complement existing Departmental strengths in volcanology, geodynamics, paleoclimate and climate-change hazards, and water and the environment. This position is part of a cluster hire that includes the Department of Civil, Structural, and Environmental Engineering, and the School of Architecture and Planning, aimed at enhancing research and education in community resilience in the face of natural and climate-change hazards. The successful candidate is thus expected to work across the University to build interdisciplinary approaches to strengthen societal resilience to geological hazards, including with existing expertise in resilient infrastructure engineering, urban planning, communications, and crisis management. To facilitate this integration, the successful candidate will be a core member of the Center for Geological and Climate Hazards Advisory Committee.

MINIMUM QUALIFICATIONS: Candidates must hold a doctorate in geology or a closely related field. Candidates must demonstrate excellence in research, teaching, service, and mentoring. Candidates should be internationally recognized scholars as evidenced by impactful publications and a sustained externally funded research program.

PREFERRED QUALIFICATIONS: Demonstrated highly productive and creative record in geological or climate hazards research.

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The ideal candidate would be a systems level thinker with strong quantitative skills. We are seeking an individual with a diverse background who would use these skills to investigate and quantify the interaction of soil microbial community composition and metabolic activities and their subsequent influences on nutrient cycling and availability for plant uptake/biological activities. Using a systems approach, research on the interplay of root exudates, temperature, CO2, water/soil pore system and soil management on nitrous oxide, methane and CO2 emissions will lead to mathematical and conceptual models of the soil biosphere. These models will consider root growth, plant nutrient use efficiency, carbon budgets, water, the macro- and microbiological components and their activities and other important components of the soil ecosystem. Information and data will be linked with existing above ground mechanistic models of crop growth for evaluation of management effects on both soil health and sustainability and crop production resiliency. The incumbent will work collaboratively with highly recognized and cutting edge scientists from other USDA-ARS laboratories to obtain experimental data regarding soil biological processes from multiple locations. The incumbent is also responsible for planning research activities, reporting to customers and scientific peers, and supporting technology transfer of products developed during research.

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This announcement is open from **3/29/2023** to **4/27/2023**. To view the announcement and/or to apply, please go to **https://www.usajobs.gov** and search for announcement **ARS-D23Y-11900870-MDK**.

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Dear AGU:

In the middle of a coastal wetland in Erie, Mich., the "Great Sulphur Spring" stands out as a striking hydrogeologic feature. Here, amid karst geology, a circular sinkhole approximately 50 meters wide and 13.5 meters deep, vents anoxic and sulfur-rich groundwater. These modern-day conditions are similar to those found in the ancient seas that harbored Earth's earliest life forms. Our mission this day was to find out whether the bottom of the Great Sulfur Spring was inhabited by microbial mats, or communities where chemolithotrophic and photosynthetic microbes live together in a thin layer atop the sediment. Presumably, similar mat communities were responsible for oxygenating Earth's early biosphere.

To prospect for microbial mats, we used an underwater camera on a cable, hung from an inflatable raft. By stretching a rope across the diameter of the spring, we pulled the raft to the deepest point of the sinkhole, where the denser groundwater pools. Here, we dropped a multiparameter probe to characterize the groundwater and collected water and mat samples for analysis. Footage gathered from the underwater camera showed purple-colored microbial mat "lawns" growing at the bottom of the sinkhole. Future studies will compare these mat communities with those found in similar refugia elsewhere such as submerged sinkholes in Lake Huron, sulfur springs in Florida, and permanently ice-covered glacial lakes in Antarctica.

—**Davis Fray, Collin Toth, Sarah Hamsher, Ian Stone, Anthony Weinke, Nate Dugener** and **Bopi Biddanda,** Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich. (https://www.gvsu.edu/wri/)

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