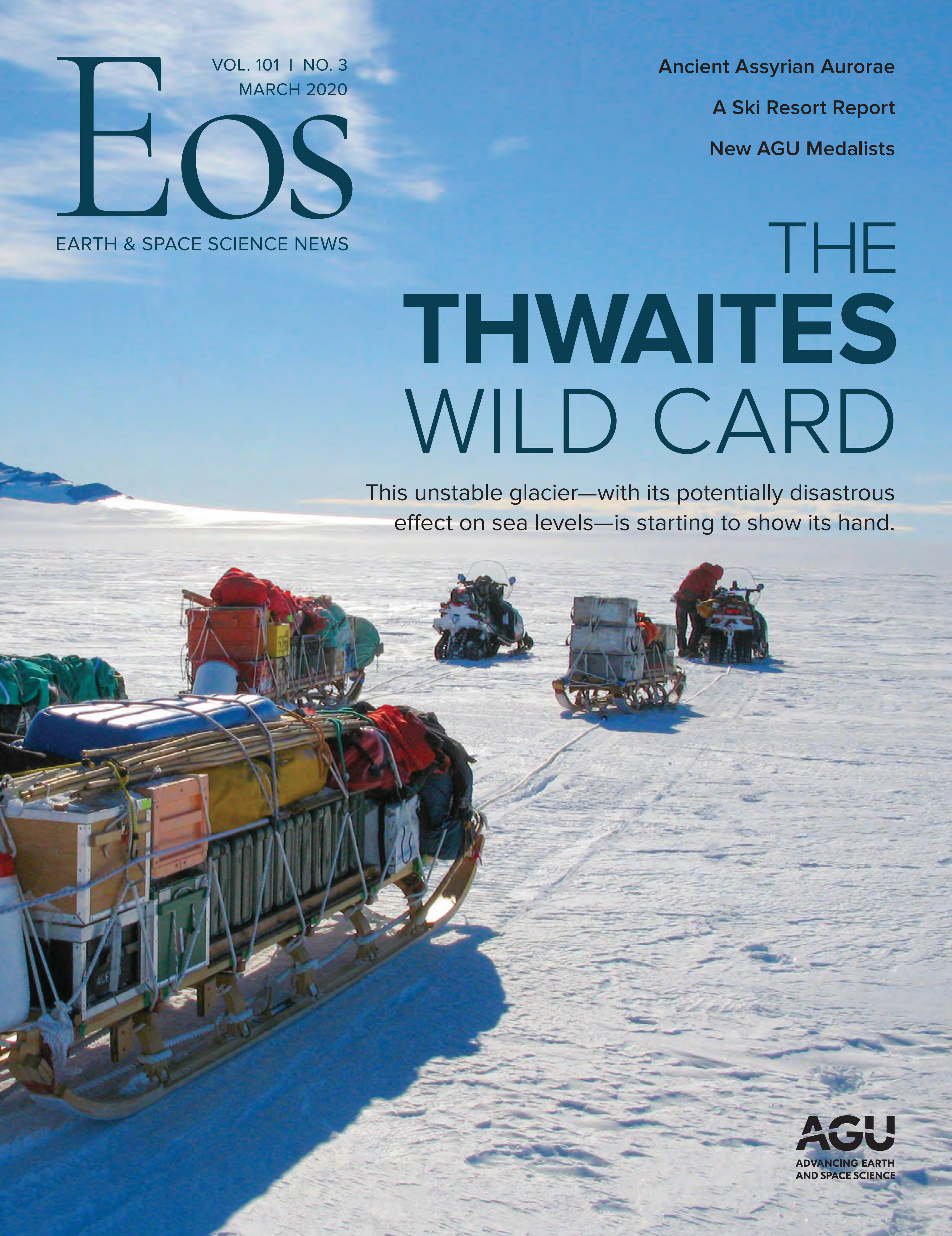

VOL. 101 | NO. 3
MARCH 2020

Eos

EARTH & SPACE SCIENCE NEWS

Ancient Assyrian Aurorae

A Ski Resort Report

New AGU Medalists

THE THWAITES WILD CARD

This unstable glacier—with its potentially disastrous effect on sea levels—is starting to show its hand.

AGU
ADVANCING EARTH AND SPACE SCIENCE

The Threat at Thwaites

The best—or at least most entertaining—thing I learned from this issue is that glaciers tend to behave "like pancake batter on a frying pan." Ted Scambos offers that description in this month's cover story, "Diagnosing Thwaites" (page 18).

Scambos is the lead scientific coordinator for the U.S. side of the International Thwaites Glacier Collaboration (ITGC). Launched in 2018, this large research initiative hosts eight teams studying the past, present, and future of Thwaites, one of Antarctica's most unstable glaciers. The problem with Thwaites, and the West Antarctic region generally, is that it's like pancake batter sliding around in too much oil—as it loses mass from both above and below, ocean water is creeping in underneath and reducing the friction between the ice and the bedrock, allowing it to slide freely over the water. The more it flows, the faster it may calve ice, and scientists have serious worries that this will create a runaway situation called marine ice sheet instability.

It will not surprise you that a catastrophic collapse at Thwaites could have alarming effects on sea level rise worldwide. That's why the ITGC teams are spending four austral summers drilling into the ice, collecting bedrock samples, and building model after model to help the experts get a grip on what is happening there.

Of course, there are challenges that come with studying unstable ice at the bottom of the world, and sometimes you must address them by blowing up things in Texas. On page 4 ("Controlled Explosions Pave the Way for Thwaites Glacier Research"), read about one of the ITGC teams trying to study the bedrock underneath the ice. They can "basically create X-ray images of the landscape" by detonating explosives near the surface of the glacier and mapping how the seismic waves propagate, says the lead scientist on the team. If you'd like to learn more about how bedrock affects glaciers generally, head to page 13 ("What Lies Beneath Is Important for Ice Sheets") to meet some researchers gaining insight into glaciology and ice vulnerability by reconstructing the topography under Antarctica back *34 million years.*

Elsewhere in the issue, we hope you'll turn to page 14 ("Understanding Our Environment Requires an Indigenous Worldview") to learn about ice—this time in Alaska—from a different perspective. Raychelle Daniel, of Yup'ik descent, describes the consequences of conducting science and creating science policy without the unique contributions of the Indigenous people immersed in the environment. Daniel's article was the excellent conclusion of a weeklong series of articles on diversity perspectives published at Eos.org. Find the entire series at bit.ly/Eos-diversity.

See you all next month.

Heather Goss, Editor in Chief

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Christine W. McEntee, Executive Director/CEO

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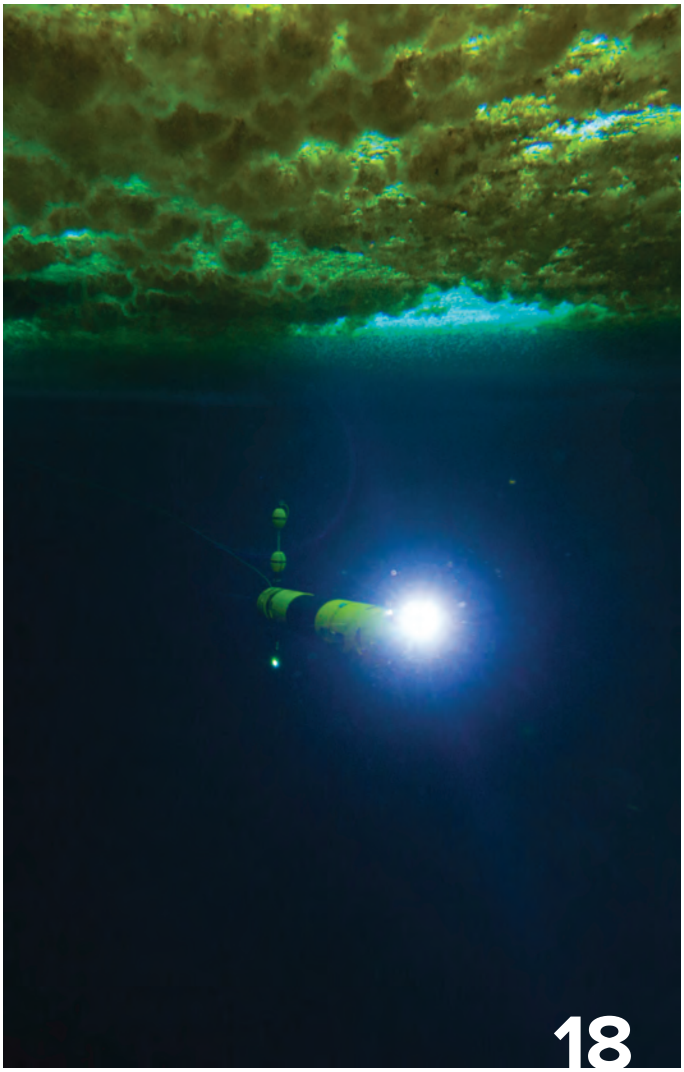
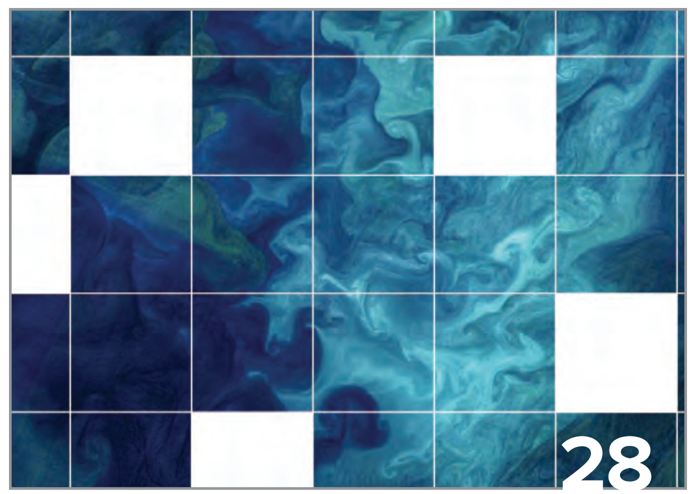
AN ENVIRONMENTALLY FRIENDLY INK SYSTEM AGRIWEB





Cover Story

On the Cover

Sledges carry scientific equipment and other supplies during a full camp move for a project team of the International Thwaites Glacier Collaboration on 25 December 2019. Credit: Joanne Johnson

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Controlled Explosions Pave the Way for Thwaites Glacier Research

There's remote, and then there's Antarctic remote.

Thwaites Glacier, located over 1,500 kilometers from McMurdo Station, falls squarely in the latter camp. An international collaboration is currently studying this notoriously unstable glacier and the significant sea level rise that would result from its collapse. And recent fieldwork in West Texas, a world away, is informing that research.

Last year, researchers working near the city of Tornillo, intentionally detonated a series of explosives mounted atop poles. The shock waves created by the detonations sent seismic waves into the ground. This technique, known as active source seismic, allows scientists to infer properties of the subsurface based on how those seismic waves propagate.

Later this year, researchers working in Antarctica will use this method to study Thwaites. Thwaites is currently responsible for about 4% of sea level rise worldwide. Some scientists believe that if Thwaites collapsed, the entire West Antarctic Ice Sheet might destabilize and break apart, boosting sea levels by more than a meter.

The Edges of a River of Ice

In November 2019, roughly 100 scientists and support staff departed for Antarctica as part of the International Thwaites Glacier Collaboration. (See our cover story on p. 18.) This consortium, funded by the U.S. National Science Foundation and the United Kingdom's Natural Environment Research Council, consists of eight different projects. One of those is Thwaites Interdisciplinary Margin Evolution (TIME), an endeavor to better understand the boundaries (the margins) of the glacier. The size of Thwaites dictates how much ice is flowing into the sea, said Slawek Tulaczyk, a glaciologist at the University of California, Santa Cruz and lead principal investigator of the TIME project. But because Antarctica is blanketed in ice, glaciers are defined only as rivers of ice that flow within slower moving ice masses, Tulaczyk said. "These boundaries can move. It's not a very stable situation."

That's where active source seismic comes in. By detonating hundreds of explosives near the surface of Thwaites and mapping how the seismic signals propagate, it's possible to "basically create X-ray images of the landscape that's sitting beneath the ice," said Tulaczyk. That's important because the margins of Thwaites might be dictated by changes in the geology of the subsurface, researchers believe.

Hot Water in a Cold Place

The traditional way of doing active source seismic in Arctic or Antarctic environments involves drilling tens of meters into the ice, placing an explosive, and detonating it remotely. But all that drilling is a highly fuel-intensive process because a steady stream of hot water is necessary to melt the ice, said Steven Harder, an explosion seismologist at the University of Texas at El Paso. "The limitation becomes the amount of fuel you can transport to the field."

In 2018, Harder and his colleagues experimented with another technique, one that didn't require any drilling and had, in fact, been used in the 1930s in Antarctica. Known as Poulter shooting, after Thomas C. Poulter, the physicist who developed it, the method involves detonating explosives mounted on poles above the ground rather than sunk deep into the ice. Harder and his colleagues experimented with different types of explosives—ammonium nitrate/fuel oil, ammonium nitrate/nitromethane, dynamite, and pentolite, for instance—and metal and bamboo poles 1.2, 1.8, and 2.4 meters long.

They worked in remote West Texas in the 849,840-hectare University Lands managed by the University of Texas and Texas A&M University systems. "This is a very small part of a big project," said Harder. "It's trying to figure out how we should do the bigger project."

Not Too Tall, Not Too Short

The researchers discovered that ammonium nitrate–based explosives atop 1.8-meter metal poles yielded the strongest seismic signals. The 1.2-meter poles didn't give the explosives enough time to fully detonate before the shock wave hit the ground, the team said. And the 2.4-meter poles were too tall: The gas pressure built up by the detonation was already dropping when the shock wave hit the surface, Harder and his colleagues concluded. These results were presented at AGU's Fall Meeting 2019.

In the 2020–2021 austral summer, TIME researchers will begin detonating explosives above Thwaites. Hundreds of seismometers will pick up the signals, and Tulaczyk and his colleagues will begin assembling a picture of the glacier's extent. There's a certain irony to using this technique to study the retreat of Thwaites, said Tulaczyk, because it was originally developed by the petroleum industry for oil and gas exploration. "We're stealing their ideas to help alleviate a problem they've created."

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

Ice cliffs at the northern tip of Thwaites Glacier tower over the Southern Ocean. Credit: Rob Larter

Interstellar Visitors Could Export Terrestrial Life to Other Stars

Life from Earth could spread beyond the solar system if an interstellar visitor skimmed our planet's atmosphere and picked up microbial hitchhikers. In fact, although the odds are slim, it's possible Earth has already sent out a slew of these natural probes.

Most research on panspermia, the idea that life could be carried from one world to another, focuses on the blunt-force approach: If a large enough rock slams into a planet infected with life, smaller debris could be blown off world, carrying microorganisms into space, where they could eventually collide with other worlds. But with the recent discovery of two interstellar interlopers, ʻOumuamua and Borisov, a new question emerged: Could objects like these have scooped up life from Earth's atmosphere and carried it back out of the system?

It's possible, according to new research from Amir Siraj, an undergraduate at Harvard University, and Harvard theoretical astrophysicist Avi Loeb. Their studies suggest that objects kicked out of other planetary systems, as well as long-period comets from our own solar system, could have hit the atmospheric sweet spot that would allow them to carry microorganisms beyond the heliosphere.

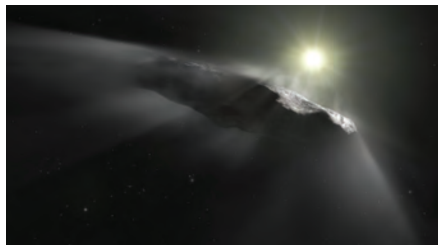
"How many objects could have come just close enough not to hit Earth but just to pick up microbes along the way?" asked Siraj.

Siraj said that he expected the answer to be zero. Instead, his research revealed that as many as 50 interstellar objects could have buzzed Earth during our planet's lifetime before leaving the solar system for good. As many as 10 long-period comets, born in the solar system and freed by the gravitational pull of passing stars, could also have escaped with life.

"We've sent the Voyager probes," Siraj said, referring to the 1970s human-made satellites on their way out of the solar system carrying information about Earth's life. "But in fact, we might have sent thousands of Voyager probes already—thousands of rocks that were laden with Earth microbes."

Catching a Ride

To pick up terrestrial hitchhikers, a comet would need to zip through the upper atmosphere, where microorganisms have been detected by other studies, but not dip low enough to burn up or collide with our planet. Previous studies have found microorganisms at up to 50 kilometers above Earth's surface, with at least one study identifying them as high as 77 kilometers. For passing comets to pick up a few microbes, higher altitude is better because the lower the comet dips, the more friction it will encounter and the more likely it is to burn up without escaping Earth's gravitational grasp.



Visitors like the interstellar comet ʻOumuamua could help spread life from Earth to other stars. Credit: ESA/Hubble, NASA, ESO, M. Kornmesser, CC BY 4.0 (bit.ly/ccby4-0)

This not-too-high, not-too-low sweet spot changes with the size and density of the objects. Larger, denser objects could survive a trip through regions lower than their more fragile counterparts.

Although hitting that sweet spot is unlikely, it's not impossible. Several atmospheric grazing events have been reported since the 1970s, the most recent being a fireball over the Australian desert in 2017. Such fireballs could have scooped up life as they passed through.

Escaping the Solar System Is Just a Start

The optimistic upper atmosphere measurements should be taken with caution, warns Manasvi Lingam, an astrobiologist at the Florida Institute of Technology. Although several studies have found microorganism colonies at altitudes of 50 kilometers, only a single published experiment has identified them at almost 80 kilometers. That experiment hasn't been replicated since it was performed in 1978. "It's a somewhat controversial paper," Lingam said. That doesn't mean the research was wrong, he said, only that it needed to be independently verified. "Until we have another subject that corroborates the results, we just need to be cautious about using those older studies."

Siraj didn't seem overly concerned, pointing out that his team was mostly interested in finding out whether the process itself was possible. He expressed optimism that studies like his might spur further investigation into how high microorganisms could survive in the atmosphere.

Hitching a ride is only the first step. Once microorganisms were outside the solar system, radiation from other stars could quickly put an end to any terrestrial life that managed to escape the solar neighborhood. That's why comets, both local and interstellar, make such good transportation. With their icy surfaces, comets are extremely porous, allowing microorganisms to burrow or be pushed into the depths rather than ride on the surface. Tucked away inside, life could be shielded from harmful radiation by its transportation.

"It's hard to know what would happen to the microbes," Lingam said, pointing out that there are few studies on how much protection the icy surface provides from radiation. "If they do make it closer to the center of the object, deep inside the object, I think they would be quite fine. It really depends on how many of them can burrow to a deeper layer."

The next step, of course, would be colliding with another habitable planet where the microorganisms could flourish. Although the odds of that aren't covered by the current paper, Siraj said he hopes to study the subject in the near future.

Impacts remain the dominant method for carrying life off Earth, but Earth-grazing objects could provide a significant addition. "This is a very small subset, but perhaps one of the most important," Siraj said.

The new research was published in January in the *International Journal of Astrobiology* (bit.ly/earthgrazing-LPC-ISO).

"We might have sent thousands of Voyager probes already—thousands of rocks that were laden with Earth microbes."

By **Nola Taylor Redd** (@NolaTRedd), Science Writer

Modern Farming Kick-Starts Large Landslides in Peruvian Deserts

Edu Taipe views the Punillo Sur slow moving landslide in the Vitor valley in Peru, which was triggered by irrigation in the late 1980s. Credit: Pascal Lacroix

In the Vitor and Siguas valleys of southwestern Peru, giant landslides have been creeping down hillsides for decades, damaging farmland in the fertile valley basins. For the first time, scientists have documented the cause of these vast movements of earth: large-scale irrigation programs developed to feed modern agriculture on the high plateaus above.

"The findings demonstrate the long-term erosional impacts of irrigation," said Pascal Lacroix, a geoscientist based in Grenoble, France, at the Research Institute for Development and colead author of the new study. "They also highlight the competition between modern and traditional agriculture."

Lacroix and his collaborator, Edu Taipe of Peru's Mining and Metallurgical Geological Institute in Arequipa, visited the valleys in May 2017, having heard of the landslides and their impacts. To investigate further, the researchers analyzed images from the Satellite pour l'Observation de la Terre (SPOT) 6 and SPOT 7 and the Hexagon spy satellite taken between 1978 and 2016.

Sleuthing the Culprit

Analyzing the satellite data, the scientists could see the expansion of cropland on plateaus above the valleys. For at least 3 millennia, farming had been confined to the basins of these valleys, where rivers provided water for crops. "But Peruvians wanted to increase the space for agriculture areas, and they couldn't do that in the valleys because they are so narrow," Lacroix said. "So they started irrigating the plateaus above the valleys."

Vast irrigation programs started in the 1950s, and satellite data detailed the expansion of farmland to cover 105 square kilometers above the Vitor valley and 76 square kilometers above the Siguas valley. During that time, satellite imagery also showed that 12 large, slow moving landslides had started, ranging in volume from 20 to 80 million cubic meters. The volume of earth moved by the largest landslide was the equivalent of more than 26,000 Olympic swimming pools.

The landslides occurred only on the sides of valleys below irrigated plateaus, and scientists found that landslides in the Siguas valley began later than those in the Vitor valley. This time difference corresponds to later development of irrigation programs in the region. "The spatial distribution of the landslides, together with the different initiation timing in the two valleys, clearly indicates that the landslides are triggered by irrigation," Lacroix said. "And when you go there, you see water gushing from the cliffs, and it is clearly from irrigation."

In both valleys, landslides began about 20 years after irrigation started, and now that earth is moving, it will continue to move, Lacroix said. The cliffs above are feeding the mechanics of the landslides and promoting motion farther down, he added.

Paradoxical Impacts

As the slides move downhill, sometimes as fast as 10 meters a year, they are eating away at agricultural land in the valleys. Satellite imagery shows that in the past 4 decades, 7% of the valley surface has been lost.

The data also show that valuable cropland on valley plateaus is being eroded as valley walls crumble. "The paradox is that modern farming needs extensive irrigation, leading to landslides, and those landslides destroy the modern farmland as well as the older farming areas," Lacroix said.

Another group of researchers, led by Paul Santi, a professor of geology and geological engineering at the Colorado School of Mines in Golden, is also investigating landslides in the Siguas valley. One of them could soon have impacts on the Pan-American Highway, a major thoroughfare, and another could eventually damage an industrial milk facility that produces approximately half the milk consumed in Peru.

Moving Toward Mitigation

Lacroix and Taipe hope their study, published in December 2019 in *Nature Geoscience*, will bring the attention of authorities and eventually lead to the deployment of mitigation strategies in the valleys (bit.ly/farming-impacts-ag). The findings show that it is important to use water efficiently, for instance, with drip or sprinkler irrigation with adequate dosing, said hydrologist Wouter Buytaert of Imperial College London. "The study highlights that rational use of water is not just a water resources issue but has wider geomorphological implications," Buytaert said.

Developing sustainable mitigation strategies requires an understanding of how irrigation is triggering earth movement. "The only way to reduce the risk of these disasters is to investigate the processes," Taipe said. "With this knowledge, preventative and mitigation measures can be implemented."

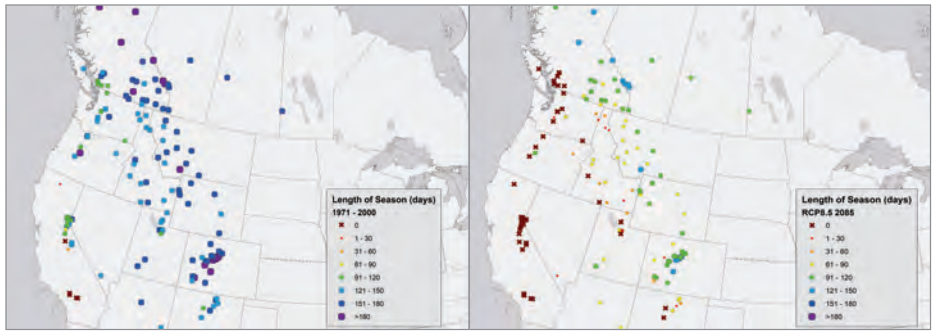
By **Jane Palmer** (@JanePalmerComms), Science Writer

Here's What Your Favorite Ski Resort May Look Like in 2085

For those living in the West, the winter of 2014–2015 went down as one of the worst ski seasons in memory. Snow levels were so low that some ski resorts didn't open, whereas others limped along with subpar snowpacks. Skiers and snowboarders at Whistler Blackcomb, a resort in Vancouver, B.C., rode trams to midmountain to reach snow.

According to new research from the University of British Columbia, the winter of 2014–2015 may become the new normal.

Climate change could significantly lower the number of skiable days across western North America, forcing some ski resorts to shut down entirely. The study, which uses historical data and model projections, forecasts that more than 90% of western resorts will have ski seasons shorter than 120 days by 2085 if countries don't curb greenhouse gas emissions. Although many more severe risks could come from climate change, losing recreational skiing, snowboarding, and snowmobiling opportunities could cost the United States billions of dollars and tens of thousands of jobs per year, according to the nonprofit Protect Our Winters.



A map of ski resorts in the United States and Canada shows the average length of ski seasons from 1971 to 2000 (left). Model results (right) reveal the decreasing length of ski seasons in 2085 under the high-emission scenario. Credit: Michael Pidwirny and Ethan Clark

"I think a lot of people can't wrap their heads around what scientists are saying about how climate change is going to change their life," said Michael Pidwirny, an associate professor at the University of British Columbia. "But a lot of people ski, and a lot of people do winter activities."

"It's kind of an interesting canary in the coal mine," he added.

Shrinking Seasons

Ski resorts need two ingredients for a good season: freezing temperatures and a healthy dose of precipitation. Pidwirny and his master's students Ethan Clark and Kalim Bahbahani investigated how climate change would jeopardize the necessary conditions for a healthy snowpack.

First, the researchers calculated baseline air temperatures at 154 ski resorts stretching from Canada to California using historic weather data. Next, they modeled future mountain temperatures with 15 different general circulation climate models seeded with two scenarios of future greenhouse gas concentrations. In one scenario, countries curb emissions and cap warming at about 2°C above preindustrial levels; in the other, countries do not act as aggressively to curb emissions, and global temperatures soar by 3°C to 5°C. These scenarios are widely used across climate sciences and come from the Intergovernmental Panel on Climate Change.

In the first scenario, only a third of 154 ski resorts have seasons longer than 120 days. Pidwirny said that some researchers regard 100 days as an economic cutoff for breaking even. In the same scenario, 21 resorts have zero skiable days, meaning that temperatures never dip below freezing to bring snow.

In the second scenario, when countries do little to curb emissions, only 9% of resorts would pass 120 days, and nearly a third of resorts wouldn't have a skiable day all season.

Not all ski resorts are affected the same, however: Resorts in coastal states fare far worse than those in inland states. In the second scenario, the only resort in Oregon with a ski season is Mount Hood, and all resorts in California have no ski seasons. Yet the higher temperatures in that scenario help some resorts in interior states like those around the Rocky Mountains because warmer subzero air can hold more moisture and produce more snow.

"Skiing is in trouble," Pidwirny said. Although there is year-to-year variability, his prediction for resorts is bleak: "For most of them, they'll shut down."

Money Melting Away

Jessica Lundquist, a professor at the University of Washington who was not involved with the research, called the latest study important and in agreement with other scientific studies. She said that one way scientists could help resorts stay open is by advancing seasonal snow forecasts.

> **"I think a lot of people can't wrap their heads around what scientists are saying about how climate change is going to change their life."**

"Ski resorts are doing their staffing early in the fall, and the ones at lower elevations need information that can let them make the hard decision of when to either delay opening or skip a winter season entirely," Lundquist said.

Ski resorts may welcome the help. If the low-snow season of 2014–2015 was any indication, shortening ski seasons will bleed money from local economies.

The team presented its research at AGU's Fall Meeting 2019 and plans to submit its results for publication. The project received funding from the Canada West Ski Areas Association.

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Ancient Assyrian Aurorae Illuminate Solar Activity

On a dark spring night, the sky blanketing the Neo-Assyrian Empire turned red. The red glow was taken as an ominous sign—one important enough that the Assyrian court scribe Issār-šumu-ēreš carved an official record of the event into a clay tablet.

Although the event, which we know today as the aurora borealis, or northern lights, wouldn't have affected the course of nature at the time, it is now helping astronomers understand our Sun and may even help protect astronauts and assets in space.

The Assyrian record is one of the earliest known observations of aurorae, dating to around 660 BCE. Aurorae are created by high-energy particles launched from the Sun, and historical records offer a way to study conditions on the Sun long before the invention of telescopes.

"Direct observations [of the Sun] span some 400 years with sunspot observations, and ground-based instrument observations are mostly within 200 years," said Hisashi Hayakawa, lead author of a new study and an astronomer at Osaka University in Japan and the Rutherford Appleton Laboratory in the United Kingdom. "To discuss the kind of less frequent, but more hazardous events [coming from the Sun], we need to expand the data coverage, like with historical documents."

Blasts in the Past

Hayakawa and his colleagues identified the records by examining ancient cuneiform tablets held in the British Museum. These tablets were carved by Assyrian court scribes, whose job was to document important happenings in the empire. They often included accounts of celestial appearances, like comets (*ṣallummû*), meteors (*kakkabu rabû*), and lunar and solar halos (*tarbāṣu*), which were thought to be omens of the future. Although most Assyrian and Neo-Assyrian tablets aren't explicitly dated, their authorship gives scholars a close idea of when the tablet was written—usually within a decade.

In the tablets studied, researchers found two references from Nineveh (a city near current-day Mosul, Iraq) and one from Babylon (built along Iraq's Euphrates River) that describe red aurorae, using terms like *akukūtu,* meaning red glow, or stating, "red covers the sky." Using the authorship of the tablets, researchers think the events happened sometime between 680 BCE and 650 BCE, a century earlier than previous records of aurorae.

This Neo-Assyrian tablet from the Library of Ashurbanipal provided researchers with what may be one of the earliest descriptions of the aurora borealis. Credit: Trustees of the British Museum, CC BY-NC-SA 4.0 (bit.ly/ccbyncsa4-0)

Documenting aurorae helps astronomers understand patterns of solar activity. Magnetic storms on the Sun can release giant plumes and jets of materials, some of which fall back into the Sun and some of which are ejected and spewed across the solar system. Particles that make it to Earth can be funneled along magnetic field lines into Earth's upper atmosphere, where they strike atmospheric particles, causing them to glow. Red aurorae, like the ones seen in ancient Assyria, are typically caused by low-energy electrons.

Because they follow magnetic field lines, aurorae are most commonly seen near the poles. But strong solar events can make aurorae visible at lower latitudes. Although today it is rare to see an aurora in the Middle East, 2,000 years ago the magnetic North Pole was much closer to Mesopotamia, hovering over the Norwegian archipelago of Svalbard instead of at its current location just 4° south of the geographic North Pole.

The newly identified records also match indirect evidence of solar activity. Since 2012, several studies have found isotope data of carbon-14 levels recorded in tree rings that suggest a strong burst of solar activity during the same time period. By adding Assyrian observational evidence to these natural archival data, scientists are better able to confirm that the event was truly a space weather event caused by an extreme solar storm.

"Comparing these data from natural archives to real historical records made by contemporary astrologers at the time is very important," said Ilya Usoskin, a space physicist at the University of Oulu in Finland who was not involved with the new research. "From it, we know that we are on the right track, because the two records match each other."

Dangerous Beauty

Although solar energetic particles can create beautiful aurorae, they can also fry electronics in telecommunications satellites and harm astronauts in space. The distance from the pole to where the ancient Assyrian observations of aurorae were made is similar to that of an event in 1989 when the power grid in all of Quebec was knocked out.

"It is likely that the [ancient] storms were considerably large," Hayakawa said. "Storms with similar intensity [today] would be harmful to modern technological infrastructures."

Understanding the historical frequency of solar storms and learning how to predict such big events are important for mitigating their effects on our tech-based society. The historical data can help astronomers model how often such extreme events occur and better assess the probability of similar extreme events.

"Direct observations from the last decades are not very useful here because they just cover too short a period of time," Usoskin said. "Such historical records are very helpful because now we know that during the last, say, 3,000 years, there were three events of that magnitude, which means that on average, we may expect such disasters to occur a few times per millennia."

Hayakawa and his colleagues recently published their analysis of the Assyrian tablets in *Astrophysical Journal Letters* (bit.ly/solar-activity-660-BCE).

By **Mara Johnson-Groh** (marakjg@gmail.com), Science Writer

The Eternal Nile Is Even More Ancient Than We Thought

If you had traveled the length of the Nile River 30 million years ago, you would have followed much the same 6,650-kilometer course that you would today. The river has been flowing from its headwaters in the Ethiopian Highlands to its mouth in the Mediterranean Sea for about 6 times longer than previously thought, its course held steady by deep-mantle currents that mirror the Nile's northward flow.

The geological evolution of the Nile River is complicated, said Thorsten Becker, a geophysicist at the University of Texas at Austin (UT Austin) and coauthor of a new study published in *Nature Geoscience* (bit.ly/sustaining-Nile-River). At least five ancestral rivers have flowed north from the Ethiopian Highlands since the Miocene. "When the river we now know as the Nile formed has been debated for some time," Becker said.

Lead author Claudio Faccenna, also at UT Austin, and colleagues took a deeper approach to deciphering the Nile's ancient history by connecting the gently tilting landscape along the river's course to a conveyor belt of mantle rock that wells upward in the south under the Ethiopian Highlands and pulls downward on the Earth's crust under the Mediterranean, keeping the Nile on a consistently northward course.

The researchers took a deeper approach to deciphering the Nile's ancient history by connecting the gently tilting landscape along the river's course to a conveyor belt of mantle rock.

The idea that mantle flow patterns can influence surface topography is not new, but the sheer scale of the Nile River drainage offers a unique opportunity to study large-scale surface expressions of this mantle-landscape interaction, Becker said. "Because the river is so long, it offers a unique opportunity to study these interactions on a landscape-wide scale."

The team first traced the geologic history of the Nile by correlating ancient volcanic eruptions in the highlands with massive deposits of river sediments transported to the Nile Delta. By combining these observations, the team was able to determine that the Ethiopian Highlands rose dramatically around 30 million years ago and have remained relatively unchanged ever since, supported by a steady upwelling of hot mantle below the mountain range.

The researchers then verified their findings using computer modeling to simulate the past 40 million years of plate tectonic activity in eastern Africa, an extremely active region due to the East African Rift system. The models indicate that a stationary mantle plume that created the highlands evolved into a sustained south to north flowing conveyor belt of mantle that mirrors the south to north gradient of the river. The topography simulated by the model was "strikingly similar" to the course of the actual Nile, Becker said, down to the locations of the famous Cataracts of the Nile—a series of six rock-choked rapids between Khartoum, Sudan, and Aswan, Egypt.

"This study links a pretty diverse set of geologic observations and embeds those findings into a state-of-the-art flow model for the mantle," said Eric Kirby, a geophysicist at Oregon State University who was not involved in the new study. "It's a very compelling combination of techniques."

"Over the past decade or two, understanding how the deep Earth influences the surface has been a burgeoning field," Kirby said, "driven by increasingly high resolution seismic images and advances in our understanding of how to relate seismic images to properties that govern mantle flow, such as temperature, viscosity, and composition."

More work will need to be done to further decipher the mysteries of the Nile, said Bob Stern, a geoscientist at the University of Texas at Dallas who was not involved in the new study. An interesting next step could involve focusing the new techniques on the Nubian Swell, a region of structural uplift that runs east to west across the river, creating the Cataracts of the Nile, Stern said.

"The Nubian Swell is a mysterious area that shows no signs of igneous activity, and yet the mantle has to be responsible for that uplift somehow," he said. The uplift also is likely to

The new study combines geological field evidence (gathered by Claudio Faccenna, above, and his team) with the latest modeling techniques to reveal new insights into the age of the Nile River. Credit: Claudio Faccenna

have occurred more recently than 30 million years ago because the rocky cataracts would have been worn down by the powerful river in that much time, he said. "It's a hard place to understand just by looking at the surface expression," Stern said. "We need to look deeper."

Becker and colleagues are also planning to use their new observational and modeling techniques to look at mantle activity under other large rivers, such as the Congo and Yangtze. "We're hoping to develop techniques of reading the topography that help us fingerprint the underlying deep-mantle processes," he said. "How does the mantle shape the landscape over time? What are the geological and geophysical constraints? These are some of the big picture questions we're trying to answer."

By **Mary Caperton Morton** (@theblondecoyote), Science Writer

Bikini Seafloor Hides Evidence of Nuclear Explosions

Seventy-three years after serving as the site of the world's first underwater nuclear test, the seafloor around Bikini Atoll in the Pacific Ocean remains scarred by finely detailed craters and littered with derelict ships.

Today an interdisciplinary team of scientists is using sonar to assess the complex submarine environment. The results provide a sobering assessment of humanity's capacity to alter nature.

"We're revealing for the first time the forest and the trees of that early dawn of the nuclear age," said Arthur Trembanis, an oceanographer at the University of Delaware who presented his team's results at AGU's Fall Meeting 2019. "Now we can see the configuration of the seabed [around Bikini] and the disposition of the many ships that were sunk."

Unleashing the Power of the Atom

In the aftermath of World War II, the U.S. Navy chose Bikini Atoll for a series of controlled nuclear explosions. Between 1946 and 1958, 23 confirmed tests were conducted in the area.

Trembanis and his team studied Able and Baker, a pair of tests conducted in July 1946 as part of Operation Crossroads. Both Able and Baker involved plutonium fission bombs with a yield of between 21 and 23 kilotons, but they were deployed differently.

The Able test bomb, nicknamed Gilda, was dropped by plane and detonated 150 meters above the lagoon and the target fleet of ships positioned there. Pressure waves from the resulting fireball depressed the ocean's surface and sank several ships.

In contrast, Baker was the world's first underwater test of a nuclear weapon. The bomb was anchored 27 meters below the surface of the lagoon and the target fleet. The Baker explosion, captured in a series of well-known images, sent nearly 2 million metric tons of water, sand, and pulverized coral skyward in a plume over 2 kilometers high.

Milky Mud and Cauliflower Features

Nuclear testing at Bikini ended in 1958. After so many years, Trembanis brought no expectations about what, if anything, he and his team might find.

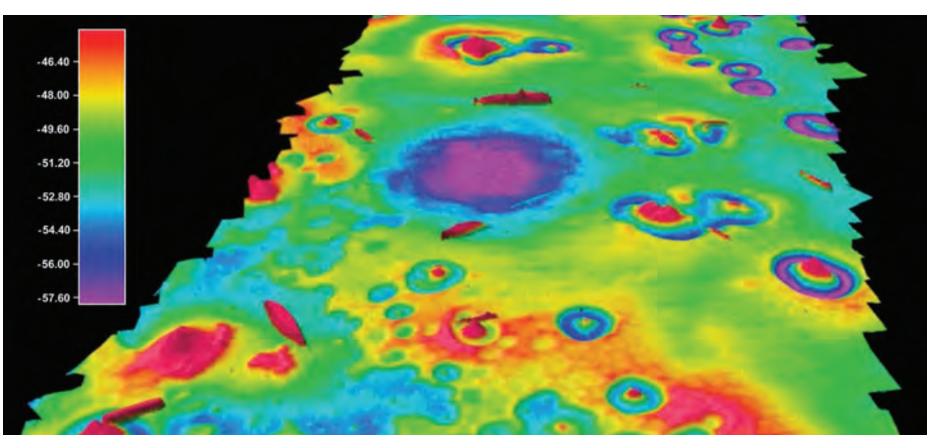
They began by using sonar to "mow the lawn," motoring a tin boat back and forth across an area 1.5 times the size of New York's Central Park. Altogether, the map represents 20 million individual points of reflected sound, the most detailed geoacoustic map of the region to date.

When scans of the Able site yielded undisturbed seafloor, it seemed time had reclaimed the evidence. But images of the Baker site revealed something unexpected.

Clustering around a laptop, Trembanis and his team witnessed the real-time rendering of an underwater crater more than 800 meters across—big enough to fit three Roman Colosseums.

Rather than a smooth bowl, radiating out from the center of the Baker crater was a series of what Trembanis called "cauliflower features" embedded in a "powdery, milky mud," testaments to the blast's immense force. He believes these structures formed as superheated debris from the cauliflower-shaped plume atop the spray column rained back down into the crater.

"If you imagine a bathtub, it would be like dumping a giant bag of sand into it," Trembanis said. "It's going to hit and then radiate away."



A geoacoustic map revealed "cauliflower features" on the Bikini seafloor beneath the site of the Baker nuclear test. The unusual bathymetric features were a result of debris that rained down from the cauliflower-shaped plume created by the detonation of Baker's plutonium fission bomb. Credit: Courtesy of Art Trembanis, University of Delaware

Ghosts of the Past

Littered throughout the atoll are the husks of decommissioned dreadnoughts, aircraft carriers, and submarines situated to bear the brunt of the Able and Baker explosions.

In addition to their seafloor mapping, which Trembanis describes as "painting the house with broad brushstrokes," the researchers performed detailed assessments of the 12 shipwrecks nearest the blast sites.

Both explosions sank vessels, flash melting ships into twisted specters. The USS *Pilotfish,* a submarine close to the Baker blast, was built to withstand several hundred kilograms per square inch. But pressure sensors deployed during the test registered pressures 10 times higher.

Following up on the sonar findings, divers were sent to six wrecks, and all showed substantial damage that could have come only from these immense explosions. The *Pilotfish* rested on the bottom, its steel rivets torn apart when its hulls breached.

Even independent of their place in nuclear history, the *Pilotfish* and other Bikini shipwrecks attest to the long-lived effects of human activities on the environment.

As old ships decompose, they become ecological burdens, and researchers found that several wrecks on the Bikini seafloor are leaching plumes of oil.

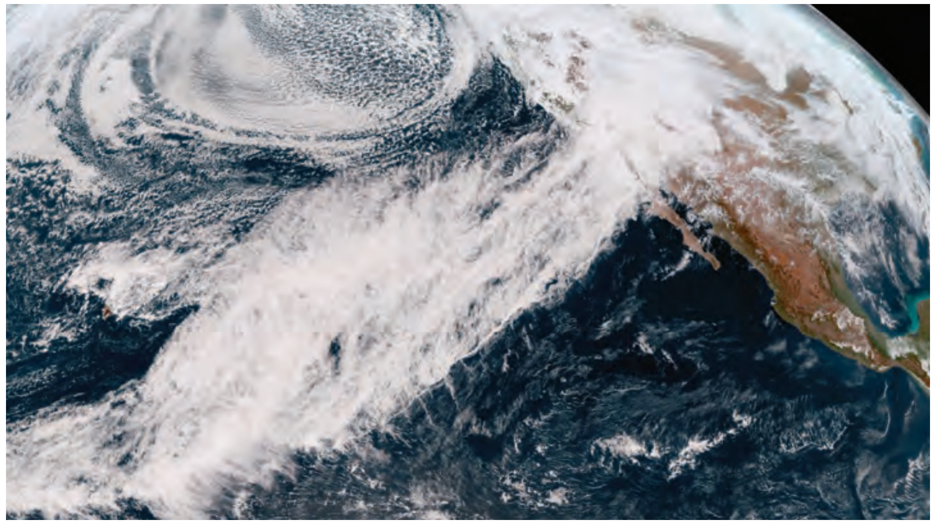
Visible and Invisible Scars

"Mapping the seafloor or shipwrecks isn't new," said Nicole Raineault, chief scientist with the Ocean Exploration Trust who was not involved in the study. "But mapping the impacts of a historical maritime event and being the first to monitor recovery add something different."

According to Trembanis, this study will serve as an important baseline for monitoring recovery: "Even though we think of the testing as having ended and gone away, the impact on both the people and the environment is still quite visible."

By **Amanda Heidt** (@Scatter_Cushion), Science Writing Graduate Student, University of California, Santa Cruz

Atmospheric Rivers Have Different "Flavors"



An atmospheric river system that drenched parts of California on 14 February 2019 is seen in this image from the National Oceanic and Atmospheric Administration's GOES-West satellite. Credit: NOAA

Atmospheric rivers are wet and windy by nature—they move vast amounts of water vapor through the sky in long, narrow bands. These features, such as the recurring Pineapple Express events that carry moisture from around Hawaii to the West Coast of the United States, often supply needed precipitation, but they can also bring flooding rains and damaging winds. Seemingly similar atmospheric rivers, though, can result in very different amounts of precipitation and wind on land, puzzling scientists and complicating forecasting efforts.

In new research looking at data from the past few decades, scientists found that each atmospheric river comes in one of four "flavors"—wet, windy, wet and windy, or neutral—depending on whether it is moisture or wind dominated. The new classification scheme should help researchers discover new insights into how atmospheric rivers affect weather on the U.S. West Coast and elsewhere, according to Katerina Gonzales, a climate scientist and graduate student at Stanford University.

"Different flavors of atmospheric rivers have different impacts," said Gonzales, who presented the research at AGU's Fall Meeting 2019. This realization "could give us better clues for what we're going to get from future storms and climate change."

West Coast Flavors

Atmospheric rivers are responsible for 30%–40%, on average, of the annual precipitation on the West Coast, with most of this coming from only a few events. Some strong atmospheric rivers carry up to 15 times as much water as the average flow at the mouth of the Mississippi River. The frequency of atmospheric river events is expected to increase with climate change, according to the U.S. Global Change Research Program's Fourth National Climate Assessment, released in 2017.

Individual atmospheric river events are generally characterized using a metric called integrated vapor transport (IVT), which accounts for water volumes and winds to assess the total amount of water vapor moving through the atmosphere in a river. But it is not uncommon for storms with similar IVT values to have different impacts on land in terms of precipitation and wind speeds, which could be the difference between muggy rains and dry, blustering gales.

The researchers wanted to find a better way of classifying atmospheric rivers to understand their diverse behavior. "You need two ingredients to get moisture transport," Gonzales said. "We're losing that nuance when we only look at IVT of atmospheric rivers."

Gonzales and her team analyzed previously published IVT data for every day that the West Coast experienced an atmospheric river between 1980 and 2015. They then parsed the IVT values into moisture and wind components. When the researchers plotted those components against one another, they found that they could categorize atmospheric rivers with similar IVT values as having high moisture and low wind (wet), low moisture and high wind (windy), high moisture and high wind (wet and windy), or average levels of each (neutral).

The researchers also found that "windy" atmospheric rivers not only showed larger extremes in surface wind speeds but also resulted in higher average precipitation both in the Pacific Northwest and in California.

Gonzales said she was surprised by the result at first. "I would have expected the moisture-dominant atmospheric rivers to [result in] more precipitation," Gonzales said. But she now thinks that "wet" storms may actually be "wind limited" and that "moisture is allowed to see its full potential" as precipitation in wind-dominant atmospheric rivers when clouds are forcibly blown against coastal mountain ranges, causing the moisture to condense into rain or snow.

Ingredients for Improving Storm Forecasts

Researchers are realizing that IVT alone is no longer enough to understand the behavior of atmospheric rivers, said Gang Chen, an atmospheric scientist at the University of California, Los Angeles who was not involved with the new research. "This study in particular tries to separate the effects of moisture and wind…and I think this separation could be useful" in providing "a better way to look into the total effect" of atmospheric river events, Chen said.

Gonzales and her colleagues hope they can use their classifications to forecast the flavors of future atmospheric river events. Preliminary data suggest that the windy atmospheric rivers that tend to dump more rain are associated with deep troughs of low-pressure systems offshore, but further research is required to build predictive models. She said she imagines a future in which water managers and public safety officials can be warned further in advance of when such storms are expected to hit land.

By **Ariana Remmel** (@science_ari), Science Writing Graduate Student, University of California, Santa Cruz

Pre-Inca Canal System Uses Hillsides as Sponges to Store Water

Lima, Peru, which lies on the dry Pacific side of the Andes Mountains, is the second-largest desert city in the world. (Cairo, Egypt, is the largest.) To endure the region's 7- to 9-month dry season, Lima's 10 million inhabitants are almost entirely reliant on water collected from the glaciated Andes or transported from the lush Amazon rain forest to the east. But the glaciers are melting, and existing dams and reservoirs, which hold a total of 330 million cubic meters of water, can quench Lima's thirst through only a single year of drought.

A team of hydrologists, engineers, and social scientists is hoping to strengthen the water security of Lima and other Peruvian cities through analysis of a 1,400-year-old nature-based system developed by pre-Inca mountain communities. The technique uses a canal system that diverts water from streams to small ponds or spreads it over rocky hillslopes that act as natural sponges. This slows the flow of water down the mountains, preserving it into the dry season.

The team's analysis determined that if the system were scaled up to its maximum capacity, it could divert, infiltrate, and recover up to 100 million cubic meters of water and increase the region's dry-season water volume by up to 33%. Lead author Boris Ochoa-Tocachi of Imperial College London presented the team's findings at AGU's Fall Meeting 2019.

Quantifying the Benefit of Green Infrastructure

Like most modern cities, Lima relies on gray infrastructure like reservoirs and dams for water diversion and storage. Gray infrastructure alone, however, has its drawbacks. It is often expensive and challenging to implement. It also has a static threshold, being unable to adapt to shifting environmental conditions.

Natural (green) infrastructure can be much more dynamic and cost-effective than gray infrastructure. Green infrastructure is a broad category that can include planting native grasses to prevent erosion and maintaining wetland health to hold and filter water. Crucially, communities can use it in addition to the dams and reservoirs already in place, amplifying their effectiveness and providing a buffer when their threshold is exceeded.

To understand the most effective ways to implement green infrastructure, researchers are examining techniques already used by Indigenous cultures around the world. But few studies quantify the hydrological effects of natural interventions like those used by Indigenous Andean mountain communities.

"Sometimes we think that scientific knowledge is more valuable than Indigenous and ancient knowledge," Ochoa-Tocachi said. "With this research, we tried to really show how both can complement each other."

Going with the Flow

Ochoa-Tocachi and his team conducted workshops, field visits, and interviews with over 100 members of a village called Huamantanga in the Andean Highlands near Lima. The village is one of the last to maintain the water-saving canals known as *amunas,* and the team was able to locate 11 operational infiltration canals through participatory mapping.

"Sometimes we think that scientific knowledge is more valuable than Indigenous and ancient knowledge. With this research, we tried to really show how both can complement each other."

Then they injected a red dye into one of the canals to track the water's progress over time. Samples from local springs showed that water from the canal was retained underground for between 2 weeks and 8 months, which means that at least some of it was stored for the entirety of the dry season.

Once they had quantified the capacity of existing *amunas,* the researchers modeled what it might look like to upscale the system and apply it to the Rímac River basin, one of Lima's primary water sources. They determined that 35% of the water flowing through the Rímac River during the wet season could be similarly diverted, increasing the river's dry-season flow by 33% at the beginning of the dry season. These effects could increase the capacity of current gray infrastructure to withstand drought conditions.

The village of Huamantanga in the Peruvian Andes continues to use and maintain 1,400-year-old amunas, *canals that preserve water, to collect and store water during the long dry season. Credit: Diego Pérez/Forest Trends*

"The beauty of Indigenous knowledge is in its specificity," said Kate Brauman, lead scientist for the Global Water Initiative at the University of Minnesota's Institute on the Environment, who was not involved in the study. "Indigenous knowledge of water management is particularly beneficial because it's closely tied to the place where it was developed, and it's been honed to be very responsive to local conditions."

Ochoa-Tocachi is hoping that his team's findings will help to inform policy decisions in the region as melting glaciers remove a previously relied upon natural buffer. "If the glaciers are retreating, the only way to counteract the loss of this buffer is through the use of natural infrastructure," he said.

Peru has embraced green infrastructure in recent years, but the projects that receive funding aren't always backed by evidence. For instance, a recent review paper coauthored by Ochoa-Tocachi found that a policy of planting nonnative trees in high-altitude native grasslands is actually decreasing, rather than increasing, water availability (bit.ly/restore-forest-cover). This year, he and his team will begin a review of the benefits of native grasses for water security and erosion prevention to incentivize their preservation.

"The work that Dr. Ochoa-Tocachi and his team are doing is critical because we need more robust evidence of exactly how effective green infrastructure is, and under which conditions," Brauman said.

By **Rachel Fritts** (@rachel_fritts), Science Writing Graduate Student, Massachusetts Institute of Technology, Cambridge

What Lies Beneath Is Important for Ice Sheets

Ice sheets blanket continents, obscuring nooks, crannies, and even mountains below. The lay of the land underneath ice sheets is not just a side note—the topography is crucially important to how the overlying ice might behave.

For years, researchers have been reconstructing the topography under Antarctic ice, essentially peering through the ice sheets with technology like ice-penetrating radar.

A team of scientists wanted to better understand how the topography changed under these continent-sized glaciers, so they worked backward, reconstructing the under-ice topography of Antarctica over the past 34 million years.

They found that over time, Antarctic topography has become progressively lower. The researchers noted that their reconstructions can provide important boundary conditions for modelers who are trying to estimate ice volumes and sea levels during past climatic changes.

Topography Matters

The ice sheets of Antarctica are big players in global sea level rise. Researchers are interested in how the East Antarctic and West Antarctic Ice Sheets behaved in the past, and they rely on modeling to reconstruct ice flows.

"Bed topography is a really important boundary condition in ice sheet models," said Guy Paxman, a geophysicist at Durham University in the United Kingdom and lead author of the new study, published in *Palaeogeography, Palaeoclimatology, Palaeoecology* (bit.ly/Antarctic-topography).

"If researchers are modeling ice sheets in deep geological time, they need to have a more realistic version of the topography than just using the present-day topography," he added.

Two big factors control how ice sheets behave: the extent of land below sea level and the slope of the bed. Both characteristics can contribute to seawater seeping under the ice, a situation that encourages the glacier to start floating, become unstable, and break up. As ice sheets become unstable, they can retreat and contribute to sea level rise.

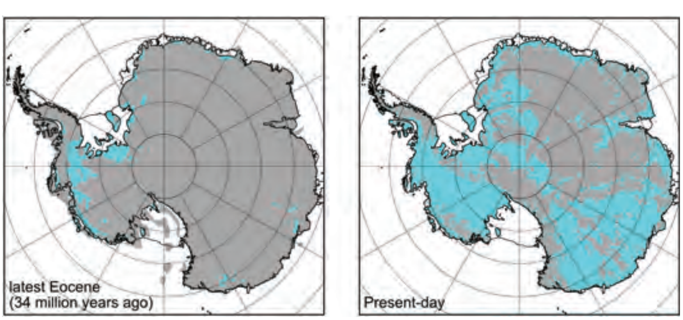
Contemporary topographic maps show that most of the bed in West Antarctica is below sea level and slopes inland. Because of that, West Antarctic glaciers such as Thwaites are of particular interest to researchers, said Dustin Schroeder, a radio glaciologist at Stanford University who was not involved with the study.

"One of the reasons we're studying Thwaites Glacier is because of its shape," said Schroeder, who added that like the Antarctic ice sheets themselves, the massive glacier could have been a big contributor to sea level rise in the past.

Bedrock Changes over Time

To better understand paleotopographic evolution in Antarctica, the team looked at four slices of time during which significant climatic changes were preserved in the geologic record: 34 million years ago (when ice started to accumulate), 23 million years ago, 14 million years ago, and 3.5 million years ago.

Paxman said their study is the first attempt to reconstruct Antarctic topography for multiple time periods beginning when ice first started to accumulate. To do that, the team had to piece together an immense amount of data on erosion, volcanism, and land subsidence from both crustal rifting and the weight of the overlying ice.



These simplified maps compare Antarctic topography 34 million years ago with the continent's present-day subglacial topography. Gray represents topography above modern sea level, and blue is topography below modern sea level. Credit: Guy Paxman

To reconstruct erosion over the past 34 million years, the researchers examined sediment accumulation around the continent. Offshore seismic data helped them reconstruct how much land was lost through erosion, and deep-sea drilling cores helped build a more complete picture of the rate of sediment accumulation.

The team found that glacial erosion rates in East Antarctica appeared to be higher during the Oligocene, the first 10–15 million years of Antarctic glaciation. Paxman noted that erosion started to slow down after the middle Miocene (about 14 million years ago).

"This is the opposite situation [of that] in West Antarctica, where erosion has picked up since the mid-Miocene," he said.

In addition to erosion rates, the team looked at ice loading and the effects of rifting in West Antarctica, including thermal subsidence. Overall, the researchers determined that Antarctica's topography has gotten progressively lower over time: 34 million years ago, there was about 25% more land above sea level than there is today.

"The most significant changes we tend to find are in the [West] Antarctic Rift system," said Paxman, but he added that there were also large changes in East Antarctica, especially in basins around margins of the continent.

Paleotopography in Practice

The new research shows that West Antarctica has changed a lot over time. "This paper said [that] in the past, the shape [of West Antarctica] was different—and really different," said Schroeder. "That is where it is provocative and interesting."

"When we do long-timescale modeling studies on these different topographies, I'm looking forward to seeing if that gives us insights into how things changed in the past," said Schroeder. He added that this work might give additional insights into how uplift and erosion could affect glaciology and ice vulnerability. "I think it really gives us a tool to ask some important questions that were much harder to ask before."

The team hopes that researchers will find the work useful for future studies. "These topographies are freely available to download," said Paxman. "We're really encouraging people [to download them]. If they want to model ice sheets in the past, these topographies are there as a boundary condition for whoever wants to look at some of these questions about past Antarctic ice sheets."

By **Sarah Derouin** (@Sarah_Derouin), Science Writer

Understanding Our Environment Requires an Indigenous Worldview

*The author, her brother Angapak Daniel, and grandmother Paiyuq Daniel after picking cloudberries (*atsaq *in Yup'ik) on a boat off the coast of their Alaskan village circa 1980. Credit: David Daniel*

I grew up in a Yup'ik village at the intersection of the Kuskokwim River and the Bering Sea in Alaska. I was named after my grandmother's father, Aluaq, and my grandmother's youngest son, Suvv'aq, or Ray. In our culture, that meant that I assumed the identity of my ancestors: I was Aluaq and I was Suvv'aq. I grew up close to my grandmother, and this relationship was important in establishing my identity as a Yup'ik woman and the values that I carry with me today.

The Yup'ik way of knowing transcends environmental observations. It includes interconnected and systematic knowledge about abiotic and biotic systems and the relationships of those systems to cultural and spiritual aspects of life. This knowledge and way of viewing the world have been evolving over thousands of years and hundreds of generations. This way of knowing informs all aspects of our society, including Yup'ik governance structures used for decision-making in spheres ranging from education and justice to natural resource management, in the same way that Western concepts of science inform federal and state governance systems, including those here in Alaska.

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These federal and state governance frameworks have been imposed on Indigenous Arctic peoples across almost all factors that influence daily life, even something as simple as where one lives. Traditionally, our peoples migrated with the changing seasons as the animals and plants shifted across the land and the sea; we moved with the salmon up the river in summer and back toward the marine mammals near the coast in winter. Places in between were visited in the spring and fall to hunt birds and forage for plants and berries.

Today's laws require physically fixed communities with schools, post offices, and airport runways. We must follow rules established by either regulations or agency policy about how fish and wildlife are managed; what information, including scientific data, can be used to inform those decisions; and who can hold the decision-making authority. Indigenous knowledge has been largely excluded from decision-making. Although our identities and well-being remain strongly connected to our environments, the decisions concerning these environments are often made thousands of kilometers away and are beyond our control.

In recent years, however, people in charge of these systems have been developing a growing awareness and interest in Indigenous peoples' knowledge systems (what we call Indigenous knowledge or traditional knowledge) and the importance of including them in the development of scientific research, policies, and natural resource management. A statement from the Arctic Observing Summit 2016 recognized the importance of including Indigenous knowledge in the framework that monitors change in the area. The National Science Foundation's Navigating the New Arctic program is drawing on diverse knowledge sources, including Indigenous knowledge, in its development stage to address challenges now facing a region radically affected by climate change.

Although these statements of inclusion of Indigenous knowledge are a start, there are significant challenges in ensuring that inclusion is done equitably. Not all of these issues can be solved quickly, but we can certainly take several steps to begin working toward a more equitable relationship between Indigenous and nonindigenous knowledge. These steps include ensuring that Indigenous peoples' voices and knowledge are involved in the concept stage of new systems; that they continue to be included in every stage of development, execution, and assessment of a project or system; and that funding is available to bring these groups from different worldviews together and ensure that Indigenous peoples and communities are paid equitably for their contributions.

All too often, there is an attempt to integrate Indigenous peoples' knowledge into existing structures and systems that were originally developed outside an Indigenous worldview. Western leadership and decision-making systems are built with a top-down hierarchy. Indigenous knowledge, on the other hand, recognizes connectivity between different roles and responsibilities within a system. When one tries to integrate a complexly interlinked system into a top-down one, cross-connections and valuable information may be missed or lost entirely.

Equitably Including Expert Indigenous Knowledge

In 1972, the U.S. Congress enacted the Marine Mammal Protection Act to protect these ocean creatures from unregulated hunting. It included exceptions for Indigenous peoples like my ancestors, who had sustainably harvested marine mammals for millennia. These animals are an integral part of our cultural practices and food security. The goal of this law is to keep these animal populations at a "sustainable" level, using an indicator of population status derived from the potential biological removal equation, which calculates how many animals can be sustainably removed through nonnatural deaths. But the mathematical equation doesn't fully take into account the worldview and immersive experience of Indigenous knowledge. The Indigenous hunter may have information about the animal's relationship to different types of sea ice, its specific habitat, or its behavior. Furthermore, the hunter's spouse, often the one who will process the animal, may have more information on the quality of the organs, the blubber layer, or the stomach contents. This combined knowledge from the hunter and the spouse is also important for determining the health of a marine mammal population, providing a more holistic view.

Even when government leaders do attempt to include Indigenous knowledge in their decision-making, that attempt to fit it into existing frameworks and research structures is often done without people who have experience in navigating both knowledge systems. When Indigenous peoples offer their knowledge, they need to understand where their information is going and how it will be used, because that information is an important part of their peoples' identity. Furthermore, without the consultation of expert knowledge holders, the meaning of the information risks being misinterpreted. Editing or changing words can risk losing their meaning. Our language is intimately tied to how we see and interact with the world. To engage with existing frameworks, we are actively translating our concepts into English language terminology that may not necessarily carry over all the important information.

For example, Yup'ik has different words across the life stages of bearded seals, and our perspective provides a conceptual map that connects those stages of life with variables in the ecosystem. Those variables might include knowledge about how the seal moves across the ocean as it forages, how a hunter has shared harvesting traits through generations, and information about seal health based on its stomach contents and the quality of its flesh or fat layer. When Indigenous knowledge is integrated into a new law or policy, the lack of expert guidance during the legal drafting process could create an untenable rule for a community that might not adequately provide protection for the animal population.

The Northern Bering Sea designation recognized the need to protect the region using the knowledge and worldview of the Indigenous peoples who call this area home.

How does one bring this equitable approach into the development of resource management or research priorities? One example is a location-based approach that brings together governing agencies and the Indigenous communities and expert knowledge holders in regular, structured conversations. In 2016, then president Barack Obama signed an executive order creating the Northern Bering Sea Climate Resilience Area in Alaska. The process began with the creation of the Northern Bering Sea Intergovernmental Tribal Advisory Council, representing over 70 tribes, that would work closely with the White House steering committee. The resulting designation recognized the need to protect the region using the knowledge and worldview of the Indigenous peoples who call this area home.

We also need to ensure that governing structures and the science they're built on are creating spaces for Indigenous peoples to participate throughout a research project or the process of federal resource management. Participation might include recruiting Indigenous research assistants from the community who collect observations or carving out time for community members to analyze data and share the results for broader feedback. Just as researchers' time is accounted for in a project, expert Indigenous knowledge holders contributing to a project should have their contributions recognized and valued in proposals. Community members may be taking time away from hunting and gathering to share their knowledge, so we must consider and appropriately compensate those members for their time.

Governance structures recognizing the inclusion of Indigenous knowledge must include providing support for the researcher, from the beginning of the project, about how to effectively engage with Indigenous peoples. The researcher may need funding and time to learn about cultures, values, and epistemologies and then time to travel and build and maintain relationships with those communities. Funding agencies need to recognize that they have the authority here to set the policy and guidelines to equitably include Indigenous knowledge and peoples.

Each of us, as individuals, is in a position to make a difference within our own organizations, and I challenge us all to facilitate a shift in our agency and academic culture to seek out equitable relationships with Indigenous peoples as we conduct our work. This shift starts with valuing the perspectives that science and Indigenous knowledge offer. In a time in which climate change is increasingly disrupting our ecosystems—along with food and shelter security in so many communities—we need all knowledge sources available if we are to adapt.

By **Raychelle Daniel** (rdaniel@pewtrusts.org), The Pew Charitable Trusts, Washington, D.C.

This article is part of a series produced in collaboration with AGU's Diversity and Inclusion Advisory Committee to highlight perspectives from underrepresented communities in the geosciences. Read the entire series at bit.ly/Eos-diversity.

Integrating Input to Forge Ahead in Geothermal Research

Scientific communities often struggle to find consensus on how to achieve the next big leap in technology, methods, or understanding in their fields. Geothermal energy development is no exception. Here we describe a methodological approach to combining qualitative input from the geothermal research community with technical information and data. The result of this approach is a road map to overcoming barriers facing this important field of research.

Geothermal energy accounts for merely 0.4% of U.S. electricity production today, but the country has vast, untapped geothermal energy resources—if only we can access them. The U.S. Geological Survey has found that unconventional geothermal sources could produce as much as 500 gigawatts of electricity—roughly half of U.S. electric power generating capacity. These sources have sufficient heat but insufficient fluid permeability to enable extraction of this heat [*U.S. Geological Survey,* 2008]. One approach to tapping these resources is to construct enhanced geothermal systems (EGS), in which techniques such as fluid injection are used to increase the permeability of the subsurface to make a reservoir suitable for heat exchange and extraction (Figure 1).

The United States and other countries have conducted experimental EGS projects since the 1970s. However, engineering a successful heat exchange reservoir in the high temperatures and pressures characteristic of EGS sites remains a significant technical challenge, one that must be overcome to enable commercial viability [*Ziagos et al.,* 2013].

Because of the great potential of this technology, the U.S. Department of Energy (DOE) is driving an ambitious initiative called the Frontier Observatory for Research in Geothermal Energy (FORGE) to accelerate research and development in EGS. The FORGE initiative will provide $140 million in funding over the next 5 years (subject to congressional appropriation) for cutting-edge research, drilling, and technology testing at a field laboratory and experimental EGS site in Milford, Utah, operated by the University of Utah [*U.S. Department of Energy,* 2018].

Assessing Challenges of Enhanced Geothermal Systems

DOE's Geothermal Technologies Office asked the Science and Technology Policy Institute (STPI) to develop a methodology for collecting input from the EGS community to produce a FORGE road map with strategic guidance for the managers and operators of the site. STPI is a federally funded research and development center established by Congress and operated by the nonprofit Institute for Defense Analyses, which provides analyses of scientific issues important to the White House Office of Science and Technology Policy and to other federal agencies.

EGS faces numerous technical challenges. These include developing drilling equipment that can withstand the heat, pressure, and geology of the EGS environment; improving the ability to isolate specific targets in the subsurface for stimulation (called zonal isolation); and learning to better mitigate the risk of induced seismicity during operations. The EGS community has a variety of ideas for how FORGE can address these challenges and for the balance needed between conducting research that is novel, though potentially risky, and efforts that will maintain a functioning site for continued use.

Technical challenges facing enhanced geothermal systems include developing drilling equipment that can withstand the heat, pressure, and geology of the EGS environment, and learning to better mitigate the risk of induced seismicity during operations.

The time frame for FORGE is also relatively short, about 5 years, especially given the substantial effort required simply to drill and establish an EGS reservoir. In light of this, STPI designed and conducted a process to capture the community's ideas for how FORGE can advance EGS, process this information methodically and impartially, and distill it into a document that is reflective of the community's input and useful for planning research at FORGE.

STPI's process was designed specifically for the FORGE road map, but the general approach described here, or specific elements of it, could prove valuable for other efforts seeking to leverage collective community feedback to move a research field forward. Using this approach, a community struggling to make progress can prioritize research and technology needs without focusing on the individual approaches of different researchers or organizations.

A Road Map for Geothermal Research

The FORGE road map, published in February 2019, is intended to offer input from the EGS research community to help the managers of FORGE craft funding opportunities, operate the site in Utah, and work toward achieving DOE's mission for FORGE: a set of rigorous and reproducible EGS technical solutions and a pathway to successful commercial EGS development.

The document outlines discrete research activities—and highlights the most critical of them—that the EGS research community proposed for FORGE to address technical challenges. The road map also categorizes all research activities into three overarching areas of focus: stimulation planning and design, fracture control, and reservoir management.

Engaging the Community

In developing the road map, STPI, in coordination with DOE, first determined categories of information that could serve as building blocks. They did this by analyzing U.S. and foreign EGS road maps and vision studies from the past 2 decades. These categories included the major technical challenges facing EGS, such as developing optimal subsurface fracture networks, and the specific areas of research that could be investigated at FORGE to address those challenges, such as testing different zonal isolation methods.

Higher-level questions included determining how progress or success could be recognized in these research areas and what accomplishments could serve as milestones for the FORGE project. Examples of potential milestones include drilling a well to a predetermined depth and measuring subsurface properties to a target resolution.

STPI then conducted semistructured interviews with 24 stakeholders from DOE, national laboratories, industry, and academia to validate and expand the initially

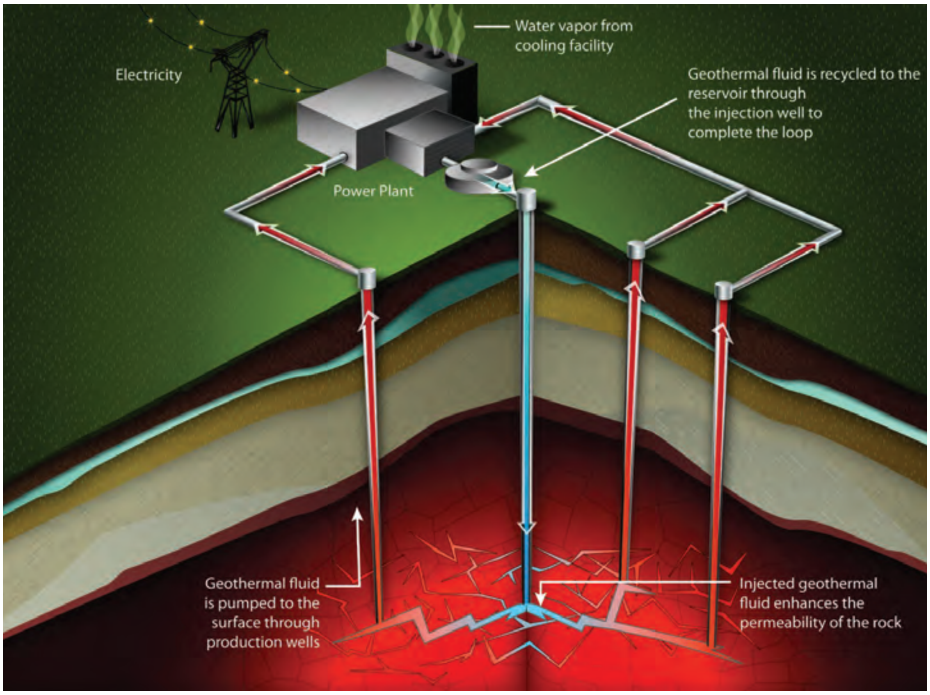

Fig. 1. A new initiative looks at new ways to tap geothermal energy resources in the United States. One approach is illustrated here. A geothermal power plant produces electricity from water that has been injected (blue pipe at center) into a subsurface reservoir, heated, and then pumped back to the surface (red pipes). Enhanced geothermal systems use techniques such as fluid injection to enhance the permeability of underground reservoirs that might otherwise not be accessible for geothermal heat extraction. Credit: U.S. Department of Energy

identified technical challenges, understand the barriers that researchers were facing when trying to address these challenges, and discuss technology that could overcome these barriers.

STPI summarized the results of these interviews, including technical challenges and potential research activities for FORGE, in an informal memorandum. This memorandum served as a preliminary, skeletal draft of the road map, and it provided the starting point for discussion in a community workshop.

In August 2018, STPI hosted a FORGE Roadmap Development Workshop at the National Renewable Energy Laboratory in Golden, Colo. Nearly 30 EGS subject matter experts from across academia, national laboratories, industry, and government attended and provided input. In a series of breakout sessions, attendees reviewed the technical challenges and research activities identified in STPI's interviews, generated a list of technical milestones for FORGE's 5 years of operation, discussed the dependencies among the research activities and milestones on the FORGE timeline, and produced qualitative and quantitative criteria to measure progress in each of the research activities.

The steps in this process—a literature review, interviews with subject matter experts, and a stakeholder workshop—represent a progression of inputs that helped elucidate EGS community perspectives on current challenges to commercial EGS development and research activities that would help FORGE solve those challenges.

Although a community may not agree on the exact path to success, having a common end point and a set of research priorities can help everyone forge ahead.

After this information had been collected, STPI worked with DOE on the technical content of the road map in preparation for its publication in February 2019. STPI and DOE consolidated, structured, and prioritized this content to provide the greatest utility to the FORGE managers and operators.

The Way Ahead

Clean, geothermal energy has the potential to make up a much larger share of the U.S. energy portfolio than it does at present, but to get there, the field of EGS will have to make substantial progress. The FORGE road map is designed to help the FORGE initiative move toward this goal as effectively as possible, especially given the variety of viewpoints on what research is most important with the limited funding and time available.

The fundamental difficulties faced by the EGS community in charting a path forward are hardly unique, and so the successful process used in developing this road map could be applicable to other research communities. Collaborative processes such as the one described here look beyond literature reviews and individual research projects, and they build on themselves as they progress. Such processes can incorporate diverging viewpoints to bring out the common challenges and potential solutions that might help a research community gain consensus on how to move forward. Although a community may not agree on the exact path to success, having a common end point and a set of research priorities can help everyone forge ahead.

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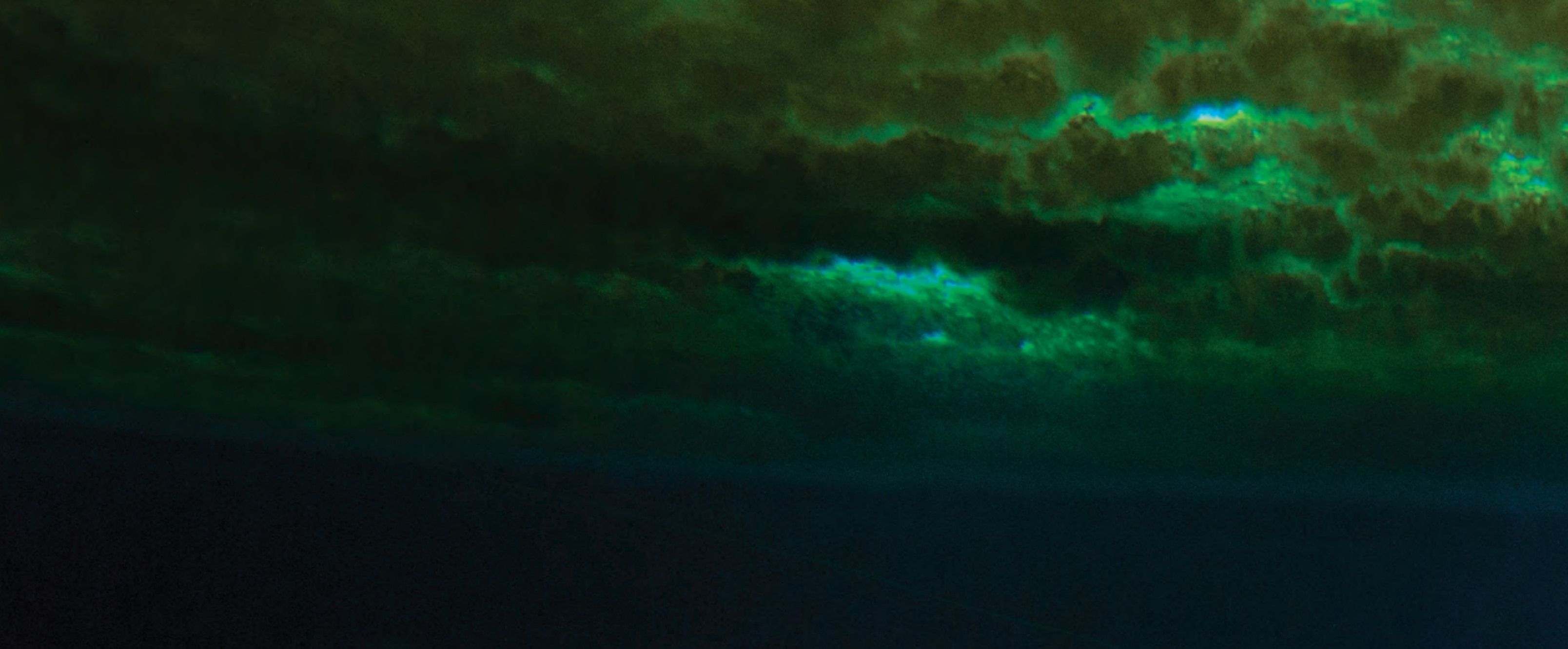


DIAGNOSING THWAITES

BY JAVIER BARBUZANO

The water under a vulnerable Antarctic glacier is warming. Its catastrophic collapse could trigger a dramatic increase in global sea level.

This advanced robot called Icefin is used to study the conditions underneath Thwaites Glacier. It recently measured water two degrees above the freezing point—unsustainable conditions for the glacier. Credit: Georgia Tech/Britney Schmidt lab

Thwaites Glacier is not stable. In fact, it is one of the most rapidly changing glaciers in Antarctica, melting at roughly twice the rate it did in the mid-1990s. And in January, scientists confirmed a dire prediction: The water underneath the glacier is currently two degrees above the freezing point.

Thwaites is a tongue of frozen water that flows from West Antarctica through a passage about 120 kilometers wide into the Amundsen Sea. Covering about 190,000 square kilometers, larger than the state of Florida, Thwaites is one of the most expansive glaciers on the continent and holds enough water to raise global sea level by more than half a meter. As with other glaciers and ice sheets worldwide, the increased melting at Thwaites is largely a response to rising air and water temperatures. But the details of why Thwaites is losing ice so fast, and what this loss might portend for West Antarctica—and for communities around the world forced to confront rising seas—are unclear.

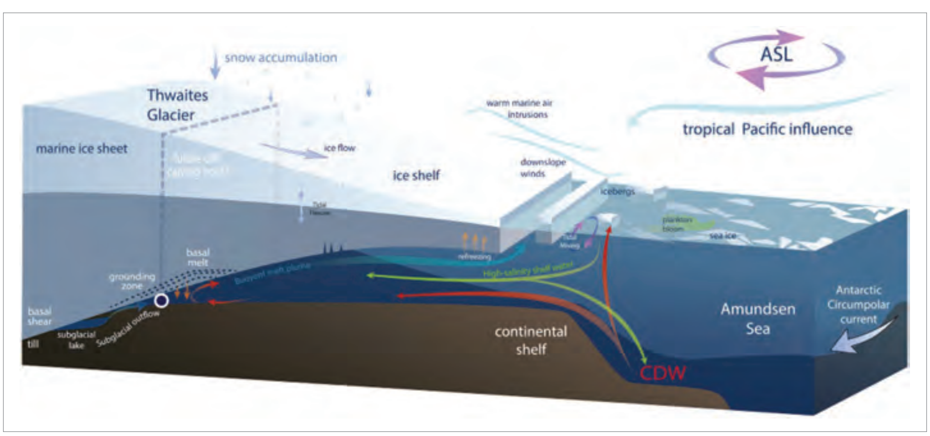
Answering these questions is a core motivation for scientists participating in a multiyear U.S.-U.K. research initiative called the International Thwaites Glacier Collaboration (ITGC), which got under way in late 2018 and is now completing its second of four austral summer field seasons. The goal of the ITGC, funded with roughly $50 million from the U.S. National Science Foundation and the United Kingdom's Natural Environment Research Council, is to diagnose the glacier's health and learn more about its history. Using data collected through the collaboration, hundreds of researchers will look at Thwaites from numerous angles, studying the ice, the surrounding ocean and atmosphere, and the bedrock beneath the glacier.

This information will allow scientists to build improved models of Thwaites's future evolution and its likely impact on sea level rise, key tools for future mitigation and adaptation efforts.

GETTING TO THWAITES

Thwaites is remote. Situated at the center of the West Antarctic Ice Sheet (WAIS), a gigantic ice mass slightly larger than the state of Alaska, the glacier stretches from hundreds of kilometers inland to the seaward edge of the ice sheet, where it discharges icebergs and meltwater. Research sites on Thwaites are more than 1,600 kilometers from the United States Antarctic Program's McMurdo Station and the British Rothera Research Station. Getting to these sites requires a 4-day trip by boat or several hours of flight and refueling stops from either of these outposts.

"Both nations felt like they had to team up in order to be able to put [forward] the kinds of resources...and the amount of equipment and gear and fuel that are needed to really explore this very large but very remote glacier in Antarctica," said Ted Scambos, a senior research scientist at the Cooperative Institute for Research in Environmental Sciences in Boulder, Colo., and



Key characteristics of Thwaites Glacier—including the ice shelf, grounding zone, and calving front—as well as drivers of change are illustrated in this schematic. Increased melting at Thwaites is due largely to incursions of warm air above and of Circumpolar Deep Water (CDW) below the glacier's floating ice shelf. These incursions are thought to be a result of changes in ocean and wind circulation in the region of the Amundsen Sea Low (ASL), a long-standing area of low atmospheric pressure. Credit: Scambos et al., 2018, https://doi.org/10.1016/j.gloplacha.2017.04.008, CC BY 4.0 (http://bit.ly/ccby4-0)

> *Using data collected through the collaboration, hundreds of researchers will look at Thwaites from numerous angles, studying the ice, the surrounding ocean and atmosphere, and the bedrock beneath the glacier.*

lead American scientific coordinator for the ITGC.

Despite its remoteness, researchers have flagged Thwaites as a scientific priority. It already contributes roughly 4% to the global sea level rise rate, currently 3.4 millimeters per year, and recent simulations suggest that it could start collapsing very quickly, within as little as 200 years, potentially adding at least 1 additional millimeter every year. Moreover, airborne and satellite observations have revealed that a huge cavity—two thirds the size of Manhattan Island and roughly 300 meters tall—is forming beneath the glacier, vacating a volume within the past 3 years that would have held 14 billion tons of ice.

Given its position amid the WAIS, were Thwaites to disappear, it could also hasten the demise of surrounding parts of the ice sheet that it helps buttress. In short, as important as Thwaites is individually, it may also be a linchpin for accelerated ice sheet collapse and melting on a much broader scale. But without a better understanding of the glacier's past, present, and potential futures, it's difficult to tell how the entire WAIS might respond to changes in Thwaites.

UNSTABLE PANCAKE BATTER

One of the reasons Thwaites Glacier is potentially unstable is the great depth of the underlying bedrock below sea level. Glaciers flow under their own weight, slowed by floating ice shelves, which act like dams for the grounded ice sheets behind, and by friction between grounded ice and the rock beneath. As Thwaites loses mass—from above and below—its ice shelf faces a greater risk of failing. In addition, the weight holding the ice sheet against bedrock lightens and ocean water can get below the ice more easily, reducing the friction and

Sledges carry scientific equipment as well as food, tents, clothing, and emergency gear for the Geological History Constraints on the Magnitude of Grounding-Line Retreat in the Thwaites Glacier System (GHC) project on 25 December 2019 during a full camp move across the ice near Mount Moses in the Hudson Mountains. Credit: Joanne Johnson

allowing the glacier to flow more freely into the ocean.

Typically, glaciers behave "like pancake batter on a frying pan," Scambos said. If you put a big blob of it on the surface it settles by flowing from the top toward the edge. "But what you get in West Antarctica is a situation where the pancake batter is on an oiled frying pan, so [the whole blob] slides over the frying pan rather than just deforming under its own weight."

If Thwaites starts thinning and flowing faster, it may begin calving—or losing large pieces of ice—at a faster rate, potentially getting into a runaway situation called marine ice sheet instability. In this scenario, the glacier's grounding line, the edge where the bottom of the ice is in contact with bedrock, retreats due to warming and the loss of ice mass. While the current grounding line is 600 meters below sea level, the bedrock farther inland is even deeper, so as the grounding line retreats, a thicker portion of the glacier will be afloat—and flow even faster under its own weight.

A waning Thwaites could also suffer from another disruptive process known as marine ice cliff instability. Previous research has suggested that ice cliffs more than about 100 meters tall are inherently unstable and can collapse under their own weight, calving off as large icebergs (although other work has questioned the potential significance of this process for Antarctic glaciers). This process could accelerate as the edge of a glacier retreats inland into thicker parts of the ice, allowing taller cliffs to form.

"We are in for sea level rise anyway because the Earth is getting warmer," Scambos said. "But if we add this wild card on top of it, we could see [sea level rise] become much more problematic, and the rate of sea level rise would become more difficult to manage."

HOLES IN THE ICE

The ITGC is divided into eight individual research projects, each devoted to studying specific scientific aspects of Thwaites Glacier and its environment. Four of the projects are looking at the natural processes that drive the glacier's retreat and its response to warming temperatures. Two are focused on unraveling Thwaites's past evolution. And two more will use what the others learn to refine numerical models that predict the glacier's future behavior.

Warmer water reaching the Antarctic coast is a major factor in the accelerated melting of Thwaites and neighboring glaciers. Changes in ocean circulation driven by shifting wind patterns—which are in turn thought to be driven by changes in distant tropical circulation—are pushing relatively warm, salty water known as Circumpolar Deep Water toward the continent from its usual location beyond the continental shelf. This warm water circulates beneath and melts the Thwaites ice shelf, the floating portion of the glacier seaward of the grounding line. For this reason, the work of many of the ITGC scientists in the field involves drilling through the ice to reach the ocean water below the ice shelf.

"We are interested in learning the temperature of the ocean water at the grounding line of the glacier," said David Holland last fall as his team prepared to head south for the season. Holland is a physical climate scientist at New York University and a principal investigator on the Melting at Thwaites grounding zone and its control on seal level (MELT) project. "We will be looking at the amount of turbulence present in the water and how vigorously it causes melting of the base of the glacier."

During the 2019–2020 field season, Holland and his team used a hot-water drill to bore 35-centimeter-wide hole through 600 meters of ice at the Thwaites grounding zone to reach the water below. It's hazardous work. "The access hole, once drilled

Aurora Basinski, a graduate student at New York University, carries a device for deployment through a borehole in Thwaites Glacier in January 2020 as part of the Melting at Thwaites Grounding Zone and Its Control on Sea Level (MELT) project. The instrument will measure water turbulence in the ocean beneath the glacier near its grounding zone. Credit: David Holland

> *If researchers find that the glacier has regrown from a partially retreated state, it might indicate that it could recover again in the future.*

through, is continually freezing back in and from time to time needs to be reamed," Holland explained. "We have to be very careful around it not to slip and fall."

Holland and his team used these holes to introduce sensors through the ice, including a state-of-the-art underwater robot known as Icefin that can explore the subsurface for several hours on each dive. Icefin can measure conductivity, temperature, depth, and dissolved oxygen, and it packs, among other instruments, a camera and an echo sounder for imaging its environment. They also deployed ocean moorings off the coast, submerged sensors that will monitor ocean conditions for over a year.

Icefin's measurements have now reported that the water at the grounding line is two degrees above the freezing point. "That is really, really bad," Holland told the *Washington Post* on 30 January when the team announced the findings. "That's not a sustainable situation for that glacier."

Scientists on the Thwaites-Amundsen Regional Survey and Network Integrating Atmosphere-Ice-Ocean Processes (TARSAN) project also drilled through the ice. They installed sensors at three locations in the water below the ice shelf, connected to surface stations by wires left to freeze in place as the holes close. These stations relay sensor measurements remotely to the researchers, who will monitor water temperature and circulation below the ice shelf to determine how currents change throughout the year. They are particularly interested in studying so-called polar water, a cool, low-salinity water layer that forms in direct contact with the bottom of the glacial ice. This layer could be disturbed by warm water coming from the ocean. "If we don't see a polar water layer there, then it means the ice is melting very fast," said Scambos, who is also a member of the TARSAN project.

A GLACIER HISTORY LESSON

Understanding how Thwaites Glacier has responded to past climate variation could tell researchers what to expect in the future.

The goal of the Thwaites Offshore Research (THOR) project is to uncover Thwaites's past from tracks that the glacier has scoured into the seafloor. Working from the R/V *Nathaniel B. Palmer,* an icebreaker operated by the United States Antarctic Program, THOR scientists are mapping and recovering sediment cores from the seafloor in front of Thwaites. They embarked on a first cruise in early 2019, and the 2020 expedition is scheduled to end on 25 March.

"We had great success last year because a lot of the landfast ice in front of Thwaites broke out from areas that have never been accessible before by ship, and we were able to extend the survey into areas we didn't expect to be able to go," said Robert Larter, a marine geophysicist with the British Antarctic Survey and a principal investigator on the THOR project.

"In these survey data, you can see features that record where the grounding line of the glacier would stabilize during periods in the past," Larter said. "So you can see these points, and you can see how [the glacier] stepped back, and see things that tell you about how the glacier was interacting with the bed and what the flow processes were."

The sediment cores allow scientists to date these events. "One thing we can look at [in the sediments] is when the contemporary retreat really started," Larter said.

Another important question regarding Thwaites's past is whether the glacier has ever retreated beyond its current grounding zone. It's been widely believed by scientists that Antarctic glaciers have slowly receded since the Last Glacial Maximum, about 20,000 years ago, although recent evidence suggests that they might have regained some ground in the past 5,000 or so years.

Finding that out is the goal of the Geological History Constraints on the Magnitude of Grounding-Line Retreat in the Thwaites Glacier System (GHC) project. If researchers find that the glacier has regrown from a partially retreated state, it might indicate that it could recover again in the future. "Essentially, the question is, If it retreats, is it always going to be in a retreated state until the next ice age, whenever that may be?" said Brent Goehring, a geologist at Tulane University in New Orleans, La., and a co-principal investigator on GHC.

Goehring and his team spent the 2019–2020 field season drilling through the ice near the margins of Thwaites glacier at its grounding zone with a portable drill used for mining exploration. Their goal was to reach shallow, volcanically formed subglacial ridges that might have been exposed to the atmosphere if the glacier retreated from its current position at some point in the past 20,000 years.

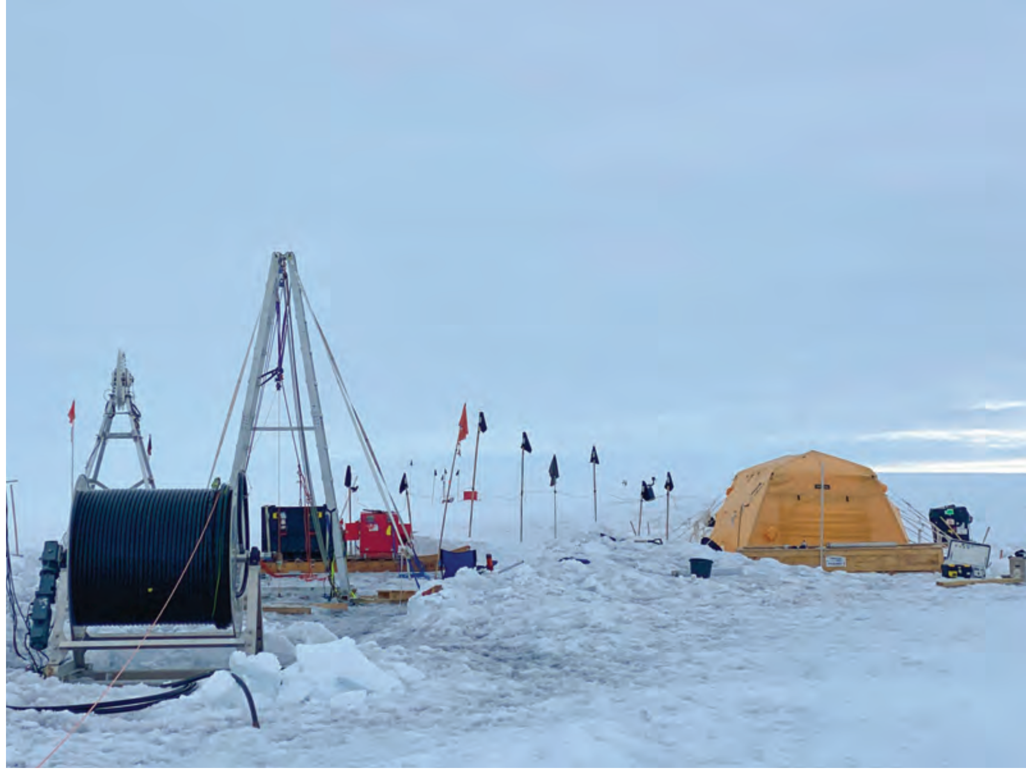
To determine whether these rocks have been above the ice level during that period, they are looking for the effects of cosmic rays, high-energy particles that constantly bombard Earth's surface from space. Cosmic rays can alter surface rocks, loading them with radioactive isotopes such as carbon-14 that scientists can measure to date when the rocks were previously exposed to the atmosphere.

If the researchers find that the ridges were above the ice at some point since the last glaciation, they can link the timing of this exposure to the sea level and climatic conditions of that time. This information will be crucial to understanding how Thwaites and other Antarctic glaciers have responded to past environmental variations.

Joanne Johnson, a geologist with the British Antarctic Survey, is the other co-principal investigator for GHC. In December 2019, she led a four-person party through the Hudson Mountains, near Pine Island Glacier just east of Thwaites, using ground-penetrating radar and sampling rocks to look for suitable drilling sites for the 2020–2021 season.

The GHC researchers must drill through 10–80 meters of ice before reaching bedrock. "Drilling into bedrock under ice is challenging," Johnson said. "In the worst-case scenario, we might not be able to recover any core! Then we might hit rock that is not what we thought it would be."

If they can recover viable rock samples, exposure dating them is no easy task either, because measuring carbon-14 in the sort of volcanic rocks that form the ridges below Thwaites is complex and not routinely done, Johnson explained. "It will also be hard working with the very small amounts of rock core that we will recover—the core diameter is about 5 centimeters, so there is not a lot of rock to work with for the people in the lab," she said.



Researchers with the MELT project set up equipment, including an A-frame structure and a winch, to deploy instruments through a borehole in Thwaites at their research site in January 2020. Credit: David Holland

SOBERING SCIENCE

The ITGC is one of the largest Antarctic research collaborations between the United States and the United Kingdom ever attempted, and it's full of challenges for researchers and their equipment.

"The whole [of the] glaciology and oceanographic communities [is] clearly challenged...by understanding [Thwaites], and challenged by the environment," Scambos said. "We are talking about drilling through the ice and then setting instruments in the ocean below the ice and having them operate for 2 or 3 years on their own. That's also a huge engineering challenge."

Brent Goehring (left) and Greg Balco, both investigators on the GHC project, work inside a lightproof bag on 1 January 2020 to collect bedrock samples from near Mount Murphy to analyze with optically stimulated luminescence dating. Credit: Brent Goehring

Researchers hope that all the effort will yield improved knowledge of Thwaites Glacier. "Hopefully the ITGC will help us fill in pieces of the puzzle so that we can more accurately describe what could happen in the future to this glacier and to global sea level," Holland said.

In addition to the personally demanding and risky frontier scientific work they are doing, ITGC researchers also worry about what the outcomes of their work could indicate about Earth's future. "There is still a lot we don't know, but this program will undoubtedly change that," Johnson said. "I went to the same sites back in 2006, so I am very excited to see the area again and see how it has changed," she said. "Probably I should not be excited about this, though, because the changes are likely to be bad news for the ice sheet's future."

In a recent review article, Ted Scambos and colleagues articulated the overarching questions very clearly, Larter noted: How much and how fast is Thwaites going to contribute to sea level rise? During the 2018–2019 field season, "we were spending whole weeks in areas where no ship had ever been before, collecting brand-new surveys of the seafloor and sediment cores," Larter said. "It's all new science, but it's also sobering to think about why you're able to be there—the very fact that it's a sign of the changes that are going on."

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Hackathon Speeds Progress Toward Climate Model Collaboration

Climate scientists collaborated in a nationwide event to analyze and compare archived Earth system model simulations and to generate input for the IPCC's upcoming climate change report.

By Wilbert Weijer, Forrest M. Hoffman, Paul A. Ullrich, Michael Wehner, and Jialin Liu

In summer 2019, scientists from the U.S. Department of Energy (DOE) gathered at six hubs across the United States to participate in a climate model comparison "hackathon." They pooled computing resources and expertise, and they collaborated in person and via videoconferencing. By joining forces, these scientists got results more quickly, reduced duplication of efforts, and spent less time solving software problems than they would have had they worked on their own.

Their findings will contribute to a sweeping report issued every 6 or so years by the Intergovernmental Panel on Climate Change (IPCC). This report reviews the state of climate change science, documents its socioeconomic implications, and identifies viable response strategies. The IPCC has produced five assessment reports so far, and the Sixth Assessment Report (AR6) is currently in preparation.

Analyses of the Earth system based on observational data from sensors on the ground, in the oceans, and in space form an important basis for these reports. But studies with computational Earth system models (ESMs) provide important complementary information because they enable insights into future environmental conditions and help attribute observed changes to specific causes.

Each model (and there are many) incorporates its own body of source data, assumptions, and algorithms. Thus, the best overall picture of Earth's climate emerges when results from several models are compared, taking note of the strengths and limitations of each. However, this type of comparison poses challenges to individual researchers.

Opposite: koctia/depositphotos.com

An Ensemble Cast of Models

ESMs capture the essential processes within the Earth system in complex computer codes. Despite researchers' best efforts, no model is perfect, because scientists must make difficult choices to balance physical realism with reasonable computational performance. It is therefore dangerous to base important conclusions about climate change on any single model.

Recognizing this, the World Climate Research Programme organized the Coupled Model Intercomparison Project (CMIP) in the mid-1990s. In this project, modeling centers run their models according to a common simulation protocol using a common set of forcings (e.g., prescribed carbon dioxide concentrations in the atmosphere).

> Models can be used to explore different narratives of future human responses to climate change, from scenarios of high greenhouse gas emissions to aggressive mitigation policies.

Scientists soon realized that they learned more by comparing model behaviors with the observed climate as well as with other models. The range of future outcomes generated by various models using different inputs provides estimates of both the internal variability of Earth's climate system and the models' structural uncertainties. Valid models can be used to explore different narratives of future human responses to climate change, from scenarios of high greenhouse gas emissions to aggressive mitigation policies that reduce emissions rates to near zero.

CMIP6: A Work in Progress

Currently, CMIP is in its sixth phase. Central to CMIP6 is a set of idealized simulation protocols called Diagnostic, Evaluation and Characterization of Klima (DECK), which are designed to enhance understanding of the climate system's response to increasing amounts of greenhouse gases in the atmosphere.

Modeling centers are asked to contribute DECK simulations first because DECK is the most basic simulation protocol. Afterward, they are free to participate in any of the other 23 other MIPs that have been approved as part of CMIP6. When CMIP6 is complete, more than 20 modeling centers around the world will have provided tens of petabytes of data produced by more than 40 models and distributed over millions of files.

The DOE's Office of Science has significant investments in ESM development, validation, and analysis. Its Earth and Environmental System Modeling (EESM) program is contributing CMIP6 simulations with its own model, the Energy Exascale Earth System Model (E3SM). This model, one of just a few completely new Earth system models introduced in recent years, saw its first release in 2018. Another program element of EESM, Regional and Global Model Analysis (RGMA), focuses on model evaluation, diagnosis, and analysis of ESMs; analysis of CMIP6 model results is an important mandate for RGMA-funded projects.

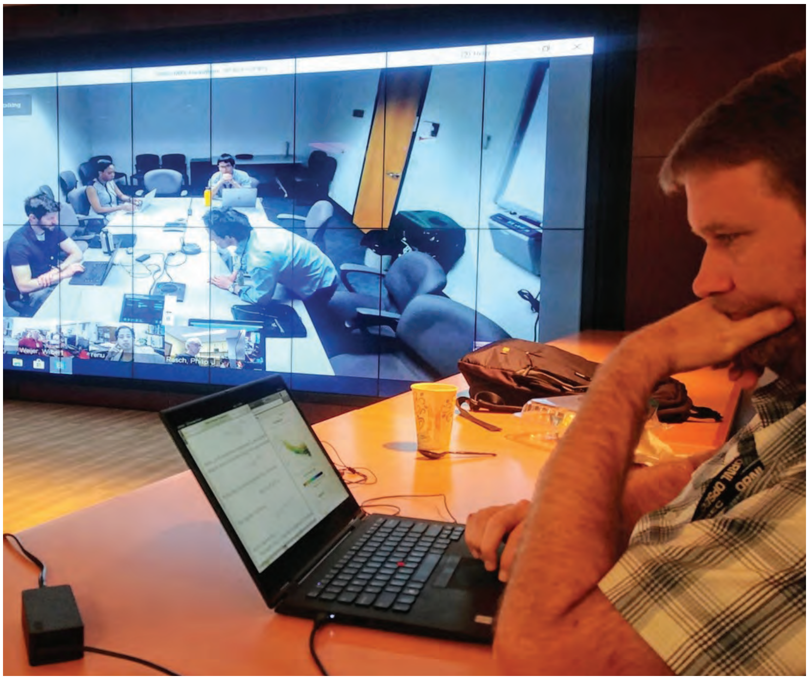
The Multimodel Analysis Challenge

For individual scientists, performing multimodel analysis can be a daunting task. First, an analyst needs access to local storage that can hold many terabytes of data, analysis and visualization software that can handle large data sets, and a powerful computing platform to perform complex computations. Second, many data processing tasks are tedious and time-consuming: identifying required data files in an online catalog, downloading and inspecting the data, noting each model's idiosyncrasies, preprocessing the data consistently through tens of models (e.g., extracting data for the time window and region of interest and calculating annual averages or anomaly time series), computing relevant metrics, and visualizing outcomes in meaningful ways. These tasks are repeated by analysts all over the world—sometimes even by multiple colleagues in the same group—representing a duplication of efforts and, often, time wasted.

During spring 2019, the authors of this article, all RGMA-funded scientists, decided that CMIP analysis could be greatly accelerated if these technical bottlenecks were managed as a group. If commonly used CMIP6 data were accessible to a large group of collaborators, directly connected to a powerful computational platform with preinstalled and tailored analysis and visualization software, then our teams could focus on producing science from the start.

From this realization, the idea for a hackathon arose. Hackathons are common events in the software engineering world in which programmers gather to collaborate intensively on a specific task. We intended for our hackathon to be an opportunity to make rapid progress in processing and analyzing CMIP6 data. We had the following goals: (1) assemble a common data cache that is quickly accessible (low latency) to many scientists from a powerful analysis platform, (2) build a common analysis environment capable of handling large data volumes, and (3) build a community of scientists collaborating toward the common goal of producing policy-relevant science.

1. We wanted to assemble a common data cache because most of the participants in this effort placed a high value on having easy access to CMIP6 data. We worked with the staff at the National Energy Research Scientific Computing Center (NERSC), the primary scientific computing facility for the DOE Office of Science, who provided us with a 2.25-petabyte disk array. Then we began downloading to this large disk array a subset of model outputs from the DECK and Shared Socioeconomic Pathway (SSP) simulations from the CMIP6 data archive that is hosted on the Earth System Grid Federation (ESGF). We downloaded data around the clock for several months and staged on the disk array a variety of observational and climate reanalysis data for use in evaluating, validating, and benchmarking the performance of CMIP6 models. We distributed a survey in



Nathan Collier, a computational Earth system scientist at Oak Ridge National Laboratory, evaluates CMIP6 model soil carbon turnover times while groups of researchers at other locations work on their own analyses during a hackathon event last summer. Credit: Forrest M. Hoffman

which participants could indicate their data needs, allowing us to prioritize the data downloads.

2. To build a common analysis environment, we promoted the use of Community Data Analysis Tools (CDAT) software developed by our colleagues in the Program for Climate Model Diagnosis and Intercomparison (PCMDI). In the lead-up to the hackathon, we provided several training opportunities to enable participants to become familiar with the analysis software, culminating in a 4-hour tutorial session presented by CDAT developer Charles Doutriaux. Even so, it seemed that the lead time was too short for many participants to familiarize themselves with the unique capabilities of CDAT, so in the end, most analysts stuck with the tools they were most familiar with: Python, MATLAB, NCL (National Center for Atmospheric Research Command Language), and others.

By fostering interactions among scientists from different projects, we hoped to facilitate exchanges of useful information and possibly initiate new collaborations.

3. With regard to building a community of scientists, several RGMA-funded projects routinely perform model intercomparisons, but other teams have less experience. By fostering interactions among scientists from different RGMA projects, we hoped to facilitate exchanges of useful information and possibly initiate new collaborations. Several days before the hackathon, we organized a teleconference during which scientists could present and discuss their analysis plans. This session gave people the opportunity to learn about their colleagues' plans, coordinate analysis tasks, and request help. This event initiated several new collaborations.

A Successful Hackathon

The hackathon was held from 31 July through 6 August 2019. Scientists worked in a collaborative and focused setting from six hubs distributed across the country. Videoconferencing capabilities enabled the hubs to remain in contact around the clock. Participants exchanged information using the messaging software Slack, and they exchanged analysis scripts using the software development platform GitHub.

Roughly 50 scientists participated in the hackathon at any given time, and about 100 RGMA scientists signed up for access to the tutorial materials, our ongoing Slack discussions, the GitHub code repository, and the data cache that we established at NERSC. Each day at 1:00 p.m. Eastern time, hackathon participants discussed their progress and challenges, one hub at a time. This daily check-in led to constructive discussions and suggestions for improving analyses and graphical diagnostics.

The coordinated CMIP6 analysis activity enabled many users to make rapid progress on meaningful science. Within 3 months, the first analyses that were initiated during the hackathon were completed. The coordinated CMIP6 analysis activity enabled many users to make rapid progress on meaningful science using the CMIP6 archive and high-performance computing resources. Within 3 months, the first analyses that were initiated during the hackathon were completed and submitted for publication, and findings were shared with lead authors of the IPCC AR6.

Many more papers are in preparation. One study, led by the lead author of this article, documents how CMIP6 models unanimously project a significant slowdown of the Atlantic Meridional Overturning Circulation, an important player in the climate system, by 2100. Other teams are studying processes like hurricanes and cyclones; monsoons; extreme precipitation events, droughts, and heat waves; Arctic sea ice; tropical forests; and the carbon cycle.

Participant feedback showed that the hackathon and associated activities were very well received among those who took part. One participant noted that the event "helped me analyze CMIP6 data more efficiently and solve software and programming issues quickly." Another noted that the hackathon "saved a lot of my time that I would have spent otherwise learning by myself." After the clear success of this event, we hope to organize similar analysis and data synthesis activities in the future.

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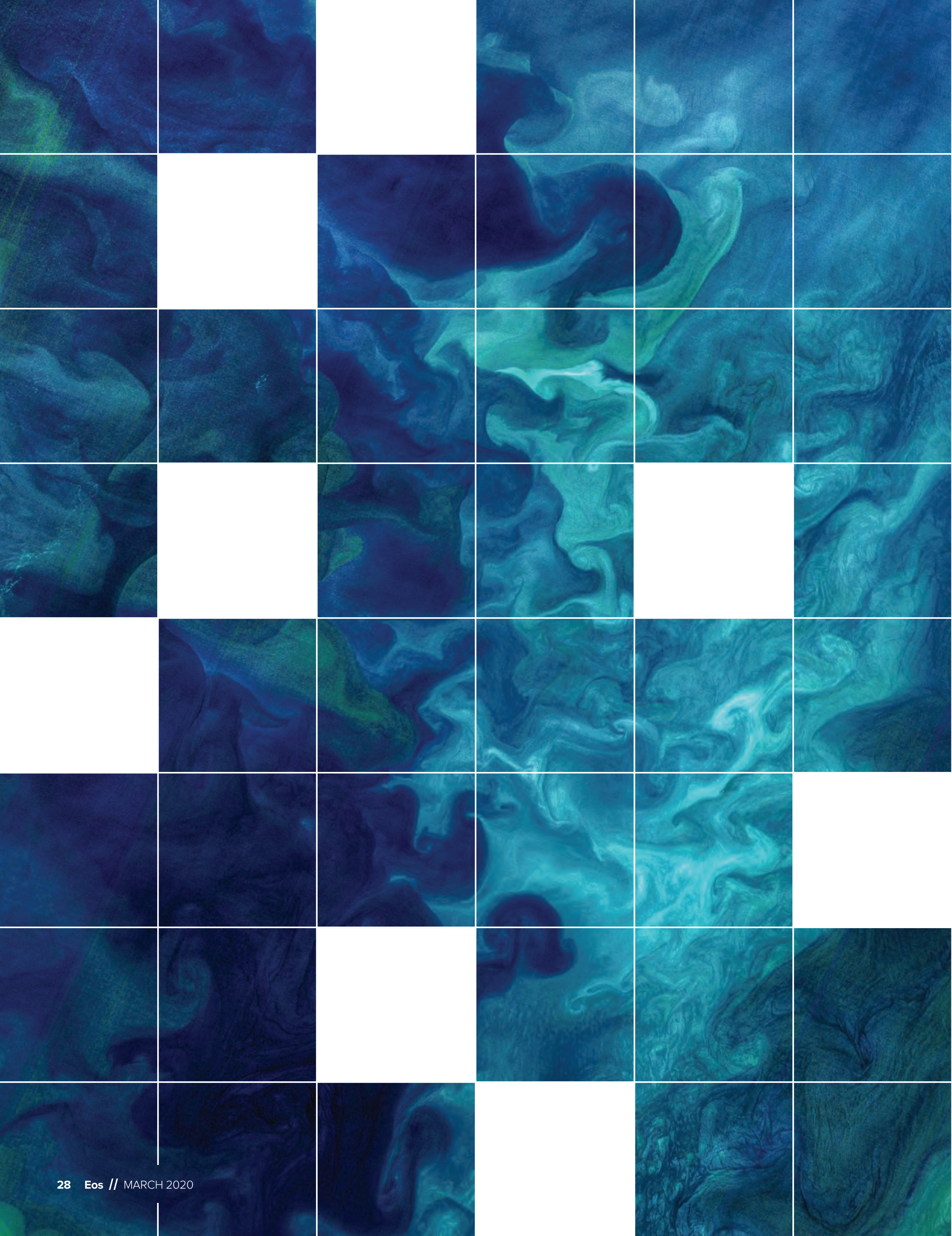
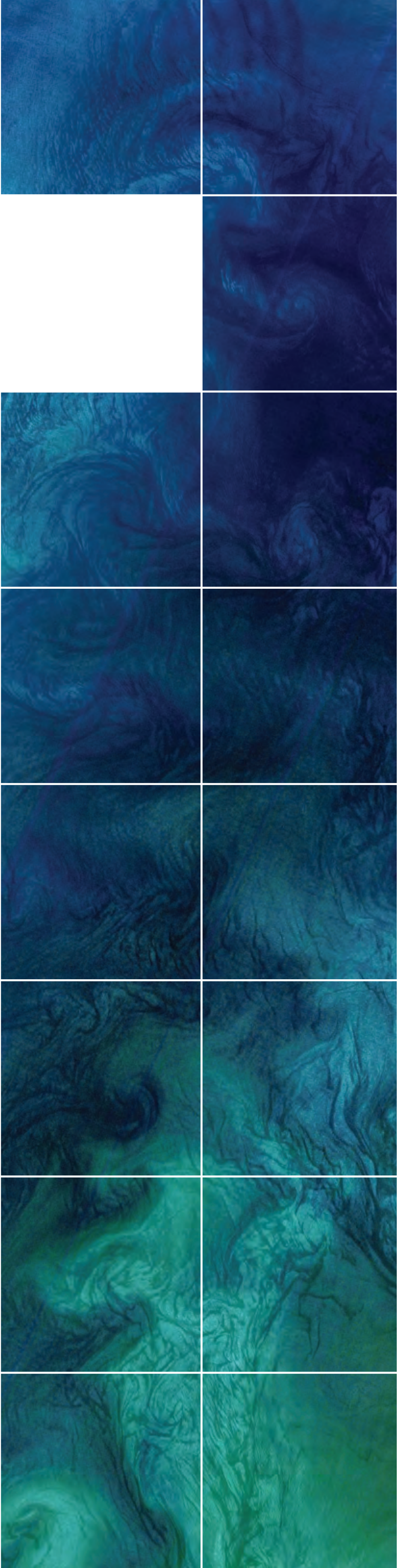
▶ Read the article at bit.ly/Eos-hackathon





Filling the Gaps in Ocean Maps

A new software application merges ocean color data from instruments aboard two satellites to provide gap-free, near-real-time monitoring of the global ocean environment.

By Xiaoming Liu and Menghua Wang

Color satellite images of the world's oceans are swirling, shifting works of art. They also provide vital information on sediment transport, plant life, and seasonal sea ice changes. As satellites orbit Earth, the instruments they carry collect detailed data on the amount of light at various wavelengths that is backscattered from ocean waters at a given location and time, and these data are compiled into color images.

The National Oceanic and Atmospheric Administration's (NOAA) Visible Infrared Imaging Radiometer Suite (VIIRS) instruments aboard the Suomi National Polar-orbiting Partnership (NPP) and NOAA-20 spacecraft provide ocean color images every day. However, cloud cover, high Sun glint, images taken from a less-than-optimal viewing angle, and other factors lead to significant data gaps in these daily images [*Mikelsons and Wang*, 2019].

Green is an important color in satellite ocean imagery. This color is related to the concentration of chlorophyll *a* (Chl *a*), a chemical produced by green plants, including phytoplankton, seaweed, and other algae. Therefore, coloration in satellite ocean images can be converted to Chl *a* concentration data, which are critical for monitoring and understanding ocean optical, biological, and ecological processes and phenomena. By merging and filling data gaps from the NPP and NOAA-20 VIIRS instruments, scientists at the NOAA Center for Satellite Applications and Research

Alaska's Chukchi Sea as observed by Landsat 8 in 2018. Credits: NASA image by Norman Kuring/NASA's Ocean Color Web, using Landsat data from the U.S. Geological Survey.

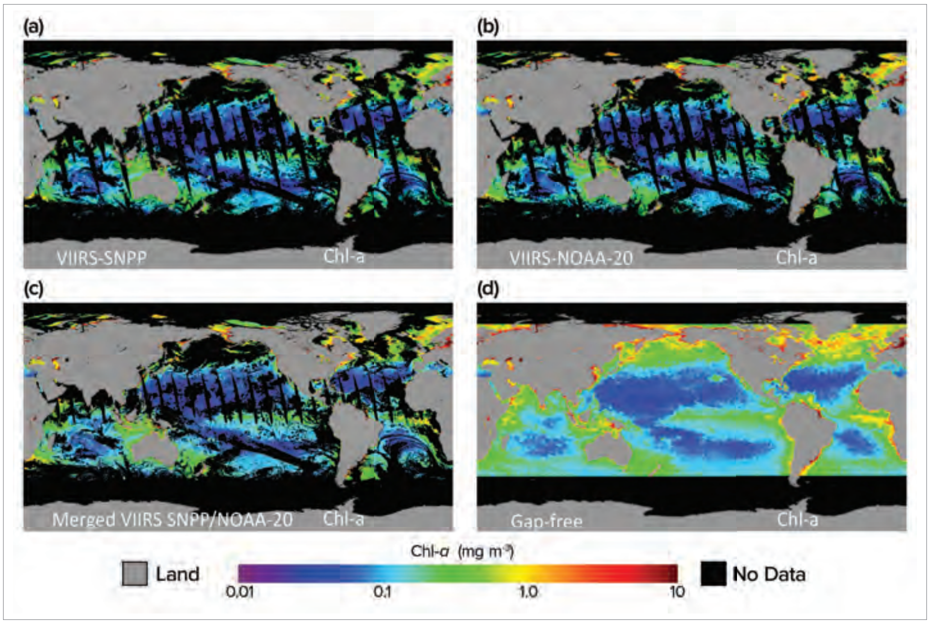


Fig. 1. This sequence of global maps shows VIIRS-measured Chl a *concentrations on 29 July 2019 from (a) Suomi National Polar-orbiting Partnership (NPP), (b) NOAA-20, (c) the merged Chl* a *image, and (d) the gap-free Chl* a *image. Chl* a *concentrations are in milligrams per cubic meter.*

(STAR) can now produce gap-free daily global ocean color Chl *a* maps that are accessible online in near-real time [*Liu and Wang,* 2019].

The gap-filling application uses a mathematical technique that exploits the coherency over location and time of the data from the two satellites to infer a value at the missing location.

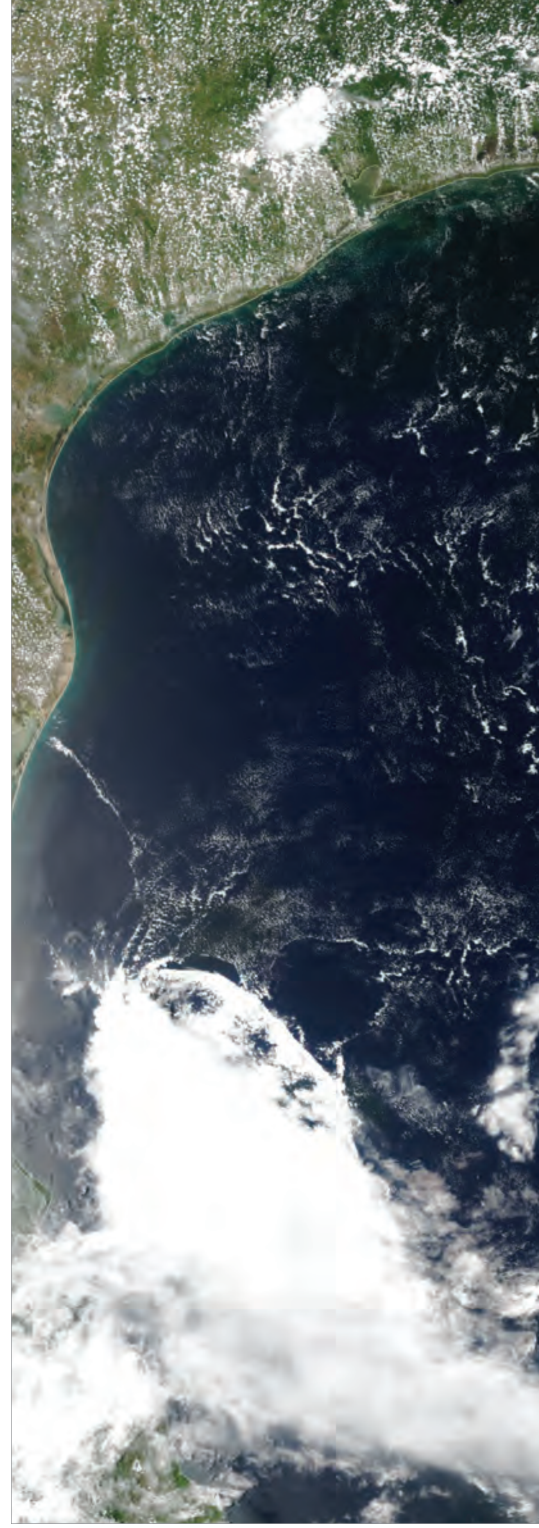
As examples, Figures 1a and 1b show global daily single-sensor Chl *a* images from NPP and NOAA-20 on 29 July 2019. About 60%–70% of the pixels in these single-sensor global daily images are missing (black streaks). These missing data make it difficult to capture dynamic ocean features in the images, so it's useful to fill these gaps before the data are used in various applications.

Merging Data from Two Satellites

NPP and NOAA-20 were launched in October 2011 and November 2017, respectively. The NOAA Ocean Color Team routinely produces global VIIRS ocean color products from both platforms using the Multi-Sensor Level 1 to Level 2 (MSL12) ocean color data processing system [*Wang et al.,* 2013].

NPP and NOAA-20 operate along the same Sun-synchronous polar orbit that crosses the equator at about 1:30 p.m. local time—both satellites travel around Earth from pole to pole in such a way that they observe the same areas at about the same time of day, no matter the season. There is about a 50-minute delay between the paths of NOAA-20 and NPP, so NOAA-20's path runs between two adjacent NPP orbital paths, and vice versa. Thus, the overlap of the spatial coverages of the two VIIRS sensors automatically fills each instrument's data gaps [*Mikelsons and Wang,* 2019]. In addition, ocean color data from both VIIRS instruments have the same spatial and temporal resolution, and these data are processed using the same algorithm and software package (i.e., MSL12). Therefore, the statistics of their ocean color products are very similar, and the data can be merged into a global 9-kilometer resolution data set directly without adjustment [*Liu and Wang,* 2019].

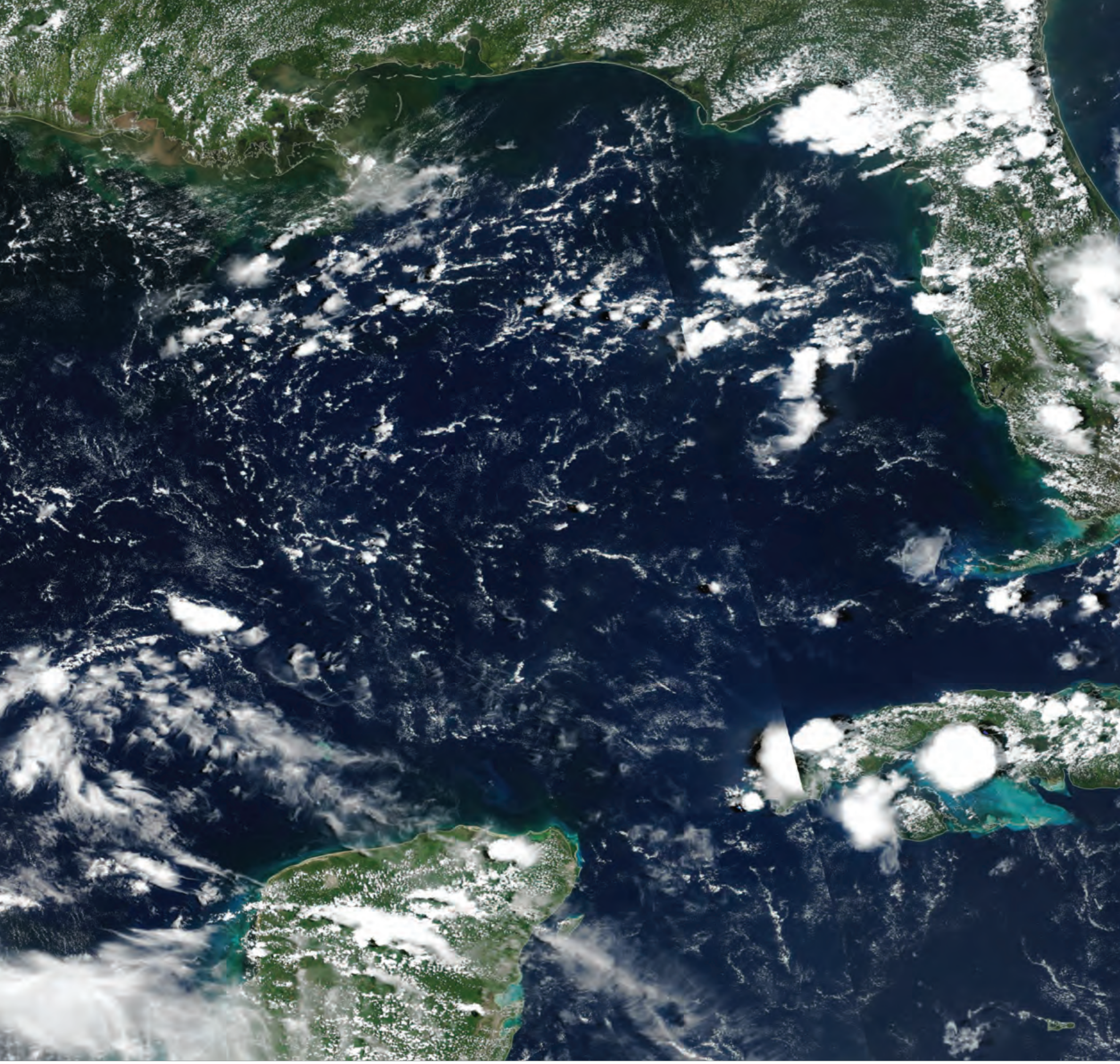
Figure 1c shows the merged Chl *a* image from 29 July 2019. In this image, the gaps of missing pixels caused by the high sensor zenith angle and high Sun glint contamination from both VIIRS sensors are almost filled. Overall, these merged data include about 38% more valid pixels than those from NPP or NOAA-20 alone.



Filling the Remaining Data Gaps

Even after the data sets from the two satellites are merged, some gaps remain. To complete the picture, the gap-filling application uses a mathematical technique based on the data interpolating empirical orthogonal function (DINEOF) [*Alvera-Azcarate et al.,* 2005; *Beckers and Rixen,* 2003]. This technique exploits the coherency over location and time of the data from the two satellites to infer a value at the missing location.

However, applying DINEOF on global-scale data requires a large amount of com-



puting resources (time and processing units), and processing a large data set requires a significant amount of computer time. We developed a time-efficient procedure that uses the DINEOF method to fill in missing pixels on the daily global ocean color images [*Liu and Wang,* 2018]. To do this, we divided the global data set evenly into 16 sections, each covering a zone with a width of 10° latitude between 80°S and 80°N, and applied DINEOF to each of the zonal sections separately. Quantitative evaluation has shown that errors in the DINEOF reconstructed data are usually within 2% [*Liu and Wang,* 2019]. We found that we could improve the data processing efficiency still further by performing DINEOF analyses on the 16 zonal sections in parallel [*Liu and Wang,* 2018].

The goal of our near-real-time operation is to reconstruct the missing pixels of daily global images within 12–24 hours of when the images were acquired. DINEOF works on a time series of data, so in our daily operational setting, we fill the missing pixels in the image of the current day using

This true-color image, acquired by NOAA's Visible Infrared Imaging Radiometer Suite (VIIRS) instrument aboard the Suomi National Polar-orbiting Partnership (NPP) satellite, shows the Gulf of Mexico on 17 July 2019. Color images like this one are used to produce data for monitoring various ocean processes, but clouds, Sun glint, and other factors can leave gaps in these data. Measurements from VIIRS instruments aboard two satellites have been merged to derive gap-free data for chlorophyll a *(Chl* a*) concentration measurements, an indicator of plant life in the ocean. Credit: NOAA/STAR Ocean Color Team*

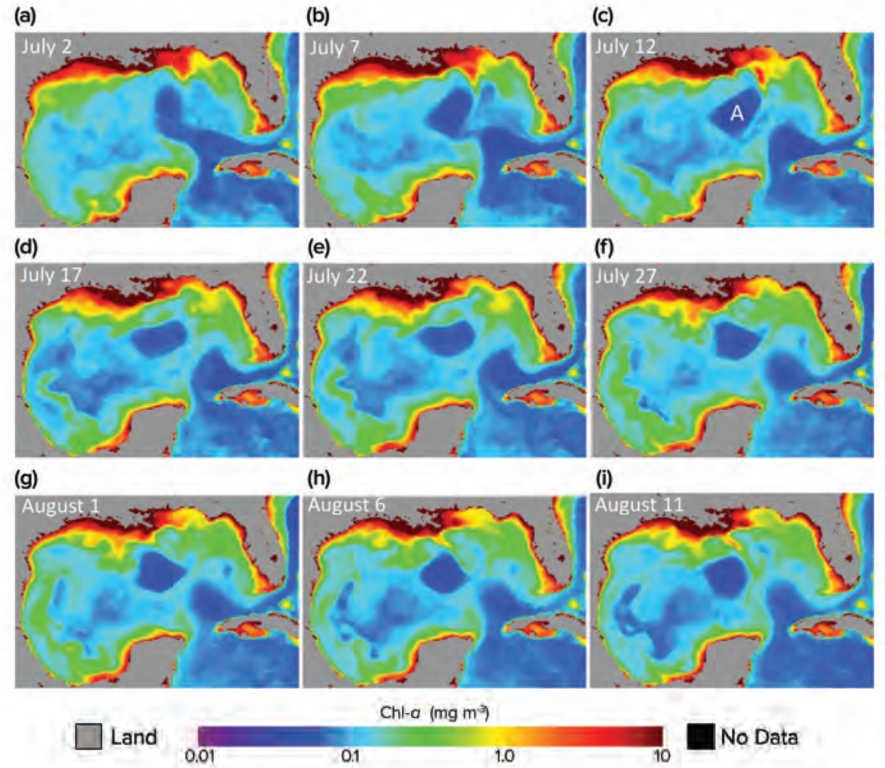


Fig. 2. This sequence of images shows daily Chl a *concentration data for the Gulf of Mexico from 2 July to 11 August 2019 with the Loop Current and a Loop Current eddy (dark blue region marked "A" in Figure 2c). Chl* a *concentrations are in milligrams per cubic meter.*

global images from that day as well as the previous 29 days.

Normally, around 7:00 each morning, the previous day's gap-free global Chl *a* image is produced using the previous 30 days of global daily merged NPP/NOAA-20 VIIRS Chl *a* images. Figure 1d shows an example of one such image on 29 July 2019 in which gaps of missing pixels are all smoothly filled. The gap filling is also very smooth temporally. To view a video showing an animation of 180 days of gap-free global Chl *a* images visit bit.ly/Eos-maps-gaps.

Large and Medium Ocean Features

Gap-free global daily Chl *a* data reveal many large-scale and mesoscale ocean features. In Figure 1d and the video referenced on the previous page, the most obvious large-scale ocean features are the nutrient-poor (oligotrophic) waters in the centers of subtropical ocean gyres and the more Chl *a*–rich waters in the equatorial and coastal oceans.

As an example of a mesoscale ocean feature, Figure 2 shows the transformation of the Loop Current and its associated eddies in the Gulf of Mexico. A Loop Current eddy, the dark blue area marked "A" in Figure 2c, spun off the Loop Current from 2 July to 12 July 2019. From 17 July to 11 August, the eddy continued to move westward while changing its shape and orientation. The transitions of these mesoscale ocean features were very smooth and can be clearly observed through the gap-free Chl *a* daily images.

The global daily gap-free VIIRS Chl *a* images can be accessed online via our state-of-the-art web application, Ocean Color Viewer (OCView) [*Mikelsons and Wang,* 2018]. The gap-free global Chl *a* data (Level-3 binned files in NetCDF-4 format) used to produce the images seen in OCView are also available upon request.

Adding More Satellite Sources in the Future

The gap-free data based on the NPP/NOAA-20 VIIRS merged products show more details in ocean features than those based on single sensors alone [*Liu and Wang,* 2019]. This result indicates that adding even more sensors into the merged products could significantly improve the quality of gap-free global ocean color data.

Currently, in addition to VIIRS on NPP and NOAA-20, the Ocean and Land Colour Instruments on the European Space Agency/European Organisation for the Exploitation of Meteorological Satellites Sentinel-3A (2016 to present) and Sentinel-3B (2018 to present) satellites and the Japan Aerospace Exploration Agency's Second-Generation Global Imager on the Global Change Observation Mission–Climate (2017 to present) are each providing unprecedented global views of ocean optical, biological, and biogeochemical properties. We are working to add these sensors into the data-merging process in the near future, which we anticipate will further improve data quality and reduce gaps in global ocean color data.

Acknowledgments

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Medalists Honored at AGU's Fall Meeting 2019

Barbara Romanowicz Receives 2019 William Bowie Medal

Barbara Romanowicz was awarded the 2019 William Bowie Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "outstanding contributions to fundamental geophysics and for unselfish cooperation in research."

Barbara Romanowicz

Citation

With 4 decades of cutting-edge work in seismology, Barbara Romanowicz has transformed our understanding of the Earth's mantle and core. She has made foundational contributions to geophysical infrastructure, and through the Cooperative Institute for Dynamic Earth Research (CIDER), she has brought together hundreds of early-career and senior scientists from across the geosciences to study Earth.

Dr. Romanowicz's research is characterized by innovative seismological theory, sophisticated numerical methods, and insightful interpretations that have illuminated key Earth processes. Using tomography to image the distribution of seismic wave velocities, anisotropy, and attenuation, she has made groundbreaking connections between large-scale Earth structure and mantle convection. She demonstrated that the two large-scale low shear wave velocity regions at the base of the mantle consist of a bundle of thicker-than-expected hot upwelling plumes connected to major hot spots at the surface and showed that the roots of some of these plumes may contain partially molten material. She also made fundamental contributions to our understanding of the continental lithosphere and how it couples to the deeper mantle, showing that continental and oceanic lithospheres are both underlain by an asthenosphere that is highly anisotropic because of shear caused by plate motion and that the mantle lithosphere of ancient cratons contains two layers of anisotropy that relate to different stages of lithospheric formation. Dr. Romanowicz has been a leader in determining inner core structure, including attenuation and anisotropy and their implications for core formation and evolution. She has also contributed innovative studies of seismic wave sources, including earthquake statistics, scaling relationships, variations in rates of occurrence of great earthquakes, and the origins of the Earth's "hum" (the continuous excitation of Earth's free oscillations).

Dr. Romanowicz has given generously of her time to build lasting and open access infrastructure for the geoscience community. She led the development of Geoscope (1981–1990), the first global network of very broadband seismic stations. As the director of the Berkeley Seismological Laboratory (1991–2011) she initiated a real-time earthquake notification system in Northern California, expanding seismic and geodetic networks and data access. She is a key advocate and pioneer of long-term ocean bottom seismic stations.

Dr. Romanowicz was the visionary driving force behind CIDER for 15 years, each summer bringing together an interdisciplinary cohort of junior and senior scientists to engage in a month of lectures, tutorials, and research projects. CIDER has created a new generation of researchers who embrace cross-disciplinary study of Earth's interior.

—**Karen M. Fischer,** Brown University, Providence, R.I.

Response

President Bell asked me to sit down before breaking the news to me—this was wise! This unexpected Bowie Medal is both an amazing and humbling honor. The only shadow is the fact that Louise Kellogg, who conominated me with Karen Fischer, is no longer with us. My warmest thanks to both of them, as well as to the other colleagues who supported my nomination.

I was fortunate to come to Institut de Physique du Globe in Paris to pursue a Ph.D. at the time when Claude Allègre was transforming it into a world-class institution. I have a connection with William Bowie: I started my research career in geodesy. High-precision measurements of Earth's global gravity field were then becoming available owing to satellite geodesy. My Ph.D. adviser, Kurt Lambeck, suggested that I use these data to build a continental-scale model of the upper mantle beneath North America, but this quickly turned into a seismic travel time tomographic model, the first at that scale. My postdoc adviser at the Massachusetts Institute of Technology, Kei Aki, wanted me to work on earthquake prediction, but I chose to play with seismic surface waves instead. Looking back from my own experience as an adviser, I appreciate their open-mindedness and patience.

With the advent of very broadband seismic sensors and digital recording, the expansion of global and regional networks, open access to large-capacity data archives, increasing computer power, and concurrent theoretical developments, global seismic imaging has made tremendous progress in the past 40 years, but we are not done. A costly and technologically challenging task is to improve coverage of the ocean floor, key to further our understanding of the connections between deep mantle circulation and plate motions, and of Earth's inner core evolution and, with it, of the geomagnetic field. We also need to continue educating ourselves and the successive younger generations across disciplines: Only by bringing together the different pieces of the puzzle can we gain a profound understanding of how Earth works. This is why we founded CIDER with Adam Dziewonski, Louise Kellogg, and Stan Hart. I wish to recognize their contributions, along with many other colleagues, to making it a successful endeavor.

My graduate students, postdocs, collaborators, and colleagues over the past 4 decades deserve to share this honor with me. I owe a big piece of this medal to my husband, Mark Jonikas, and children, Martin and Magda.

—**Barbara Romanowicz,** University of California, Berkeley; also at Collège de France, Paris

AghaKouchak, Artemyev, Fischer, Macdonald, and van Sebille Receive 2019 James B. Macelwane Medals

Amir AghaKouchak, Anton Artemyev, Emily V. Fischer, Francis A. Macdonald, and Erik van Sebille were awarded the 2019 James B. Macelwane Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "significant contributions to the geophysical sciences by an outstanding early career scientist."

Amir AghaKouchak

Citation for Amir AghaKouchak

Dr. AghaKouchak is among the most creative and productive young scientists in our profession, and his scholarship, international standing, outreach, and service to the community are widely acknowledged and admired at an early stage of his career. Dr. AghaKouchak's research accomplishments in hydrology and natural hazards and service activities provide ample evidence in the two primary criteria for the James B. Macelwane Medal: (1) depth, breadth of research, impact, creativity, and novelty and (2) service, outreach, and diversity.

Dr. AghaKouchak's research bridges the traditional disciplines of hydrology, climatology, and remote sensing to address critical global water resource issues. His research combines remote sensing techniques and physically based and statistical approaches to improve the characterization, modeling, and prediction of large-scale hydrologic systems. His group developed a multivariate multi-index drought monitoring approach, named the Multivariate Standardized Drought Indicator (MSDI). Within a short period of time, other multivariate indicators were developed on the basis of the MSDI concept. The main innovation of the approach is that it allows integrating different types of data (e.g., precipitation, soil moisture, and runoff) for composite drought assessment.

His group also developed the first methodological framework for describing socioeconomic drought. Most drought monitoring frameworks primarily focus on large-scale atmospheric–land surface conditions and ignore the human dimension. He proposed a framework for assessing water availability while explicitly considering anthropogenic water demand scenarios and water supply infrastructure designed to cope with climatic extremes. His group developed a hybrid statistical-dynamical modeling framework for improving drought prediction. In this approach, unlike previous studies where a statistical model was used for postprocessing, a dynamical and statistical model work in parallel, but they are linked through an expert advice algorithm. The uniqueness of the approach is that it combines the strength of physically based dynamical simulations and the capabilities of statistical models. Another contribution was to formulate a novel multivariate framework for evaluating the risk of compound hazards. His group showed that the current flood risk assessment methods underestimate the actual risk of coastal flooding because they do not consider the compounding effects of ocean and terrestrial flooding.

Dr. AghaKouchak has achieved an extraordinary international standing through fundamental contributions at an early stage of his career and has been very proactive in service and outreach and in promoting diversity and inclusive excellence. In just a few years, he has earned the respect and admiration of his peers, and he will continue his leadership role in the field in the future.

—Isabella Velicogna, University of California, Irvine

Response

I sincerely thank Isabella Velicogna for leading the nomination and Upmanu Lall, Balaji Rajagopalan, and Vijay Singh for supporting the case. Receiving the Macelwane Medal is a humbling pleasure, but it is not an individual recognition. It reflects the work of my amazing collaborators, students, and postdocs.

Studying and working on three continents and interacting with exceptional scientists from around the world have made my journey very exciting! When I was an undergraduate freshman, I was determined to go into design and construction engineering. An undergraduate research experience in my sophomore year with glaciologist Fariborz Vaziri changed my career path, and I became a hydrologist. I was incredibly lucky to work with Andras Bardossy and Emad Habib, who introduced me to statistical hydrology and radar science. Joining Soroosh Sorooshian's group as a postdoctoral fellow was a life-changing and inspiring experience! Soroosh introduced me to the world of remote sensing and changed my perspective toward research. I could not have imagined a more generous mentor and role model, and I cannot thank him enough for his unwavering support, encouragement, and mentorship over the years. During my postdoc, I had the privilege of collaborating with amazing scientists, including Kuo-lin Hsu, Bisher Imam, Xiaogang Gao, and Jialun Li—a great team with endless ideas!

I thank the University of California, Irvine, for taking the leap of faith to appoint me as a faculty member, where I have had the good fortune of working with a diverse group of exceptional colleagues. Special thanks go to Brett Sanders and Stan Grant for integrating me into their interdisciplinary projects and broadening my research, to Richard Matthew and David Feldman for their insights on the broader relevance of our work, to Steven Davis for sharing his brilliant mind and stimulating ideas, to Jim Randerson for his thought-provoking views, to Bill Cooper and Phu Nguyen for their stunningly positive attitude, and to Efi Foufoula-Georgiou for her critical thoughts and the opportunities she has created.

Over the past 10 years, I have had the pleasure of working and publishing with nearly 300 phenomenal scientists. I cannot possibly mention everyone here, but I would like to acknowledge the amazing interactions and stimulating discussions that I have had with Gianfausto Salvadori, Kaveh Madani, Tom Phillips, Ali Nazemi, Andy Wood, Ali Mirchi, Ghassem Asrar, Reza Khanbilvardi, Marty Hoerling, Hamid Moradkhani, Shrad Shukla, Giuliano Di Baldassarre, Jakob Zscheischler, Hamid Norouzi, Travis Huxman, Nasrin Nasrollahi, Jay Lund, Mark Svoboda, Marzi Azarderakhsh, Brian Tarroja, Chiyuan Miao, Farshid Vahedifard, Philip Ward, Thomas Wahl, Sonia Seneviratne, Jasper Vrugt, Qingyun Duan, Brian Skahill, M. R. Kavianpour, Salvatore Grimaldi, Elmira Hassanzadeh, Ali Alaiepour, Carlo De Michele, Reza Najafi, Farhad Yazdandoost, Yue Qin, and Fabrizio Durante. I have learned much from and been influenced by many more scientists than I can list here.

Most importantly, I owe this recognition to my current and former students, postdocs, and visiting scholars whom I have the honor to work with. I accept the Macelwane Medal with humility and gratitude on their behalf: Linyin Cheng, Ali Mehran, Elisa Ragno, Alireza Farahmand, Omid Mazdiyasni, Charlotte Love, Felicia Chiang, Hassan Anjileli, Alexandre Martinez, Aneseh Alborzi, Mohsen Niknejad, Lisa Damberg, Matin Rahnamay, Yunxia Zhao, Jiefeng Wu, Qiaohong Sun, Samaneh Ashraf, Carlos Lima, Zengchao Hao, Shahrbanou Madadgar, Hamed Moftakhari, Mojtaba Sadegh, Iman Mallakpour, Simon Papalexiou, and Laurie Huning. I wholeheartedly appreciate their hard work and dedication and want to thank them for their patience with me!

Finally, I am grateful for the tremendous support I have received from my parents. My heartfelt thanks to my lovely wife, Nasrin, who is an infinite source of support. Back in 2010, Nasrin and I attended the AGU Honors Ceremony for the first time. "I am sure I will see you on that stage 10 years from now," Nasrin whispered into my ear while Rosalind Rickaby was giving her Macelwane Medal Lecture. I have to admit that she has always been right! I should also mention my 6-year-old son, Kian (whose favorite magazine is AGU's *Eos*), and my almost 2-year-old daughter, Kimia, who often have to deal with my time away from home. I owe them so much!

—Amir AghaKouchak, University of California, Irvine

Anton Artemyev

Citation for Anton Artemyev

Dr. Artemyev is one of the premier plasma theorists in the world with a unique ability to work equally well with theory, models, and observations. His early work on wave–particle interactions in Earth's radiation belts was transformational. He went beyond quasi-linear theory to describe comprehensively the relative importance of particle nonlinear acceleration and scattering by strong amplitude waves, particle trapping, curved or converging magnetic fields, and high obliquity. In 2012 he established a novel theory of how kiloelectron volt energy electrons are trapped and accelerated in the oblique whistler wave potential and are accelerated to hundreds of kiloelectron volts as they move along a dipole field increasing toward the planet. He then modeled electron pitch angle scattering losses competing with the above acceleration and provided analytical estimates of electron lifetimes applicable in radiation belt models. His 2016 review paper on oblique whistler waves has already become a classic.

Since 2014, he has incorporated nonlinear effects into the evolutionary equations of plasma phase space density, previously accounting only for quasi-linear phenomena. He showed that not only whistlers but also time domain structures and kinetic Alfvén waves can nonlinearly accelerate cold electrons and that the pervasive magnetosonic waves most often also require a nonlinear description. This was a major breakthrough in our understanding of how relativistic radiation belt electrons are sourced from ambient, cold plasma electrons.

With regard to plasma current sheets, he predicted theoretically and revealed observationally that a magnetic shear develops naturally to balance the magnetic pressure external to the current sheet. He expanded prior treatments to include electron temperature anisotropy, all types of ions, and sheared fields. He advanced and observationally validated theories of particle dynamics in plasma discontinuities using his namesake Artemis mission. He observed the telltale signatures of the current-carrying ions and electron anisotropies at Earth. He then applied his current sheet theories to the Jovian and Martian magnetotails, the solar wind, and the solar corona. His 2013 review of the kinetic properties of current sheets has become a recommended read for space physics courses.

Anton is generous with his time to dozens of students, junior researchers, and colleagues all over the world alike, epitomizing AGU's motto of unselfish cooperation in research. He serves as a *Journal of Geophysical Research* associate editor, has been recognized with two citations for excellence in refereeing, and is a dynamic participant in the National Science Foundation's Geospace Environment Modeling program. His breadth of research is enviable even by senior scientists. He is a leader among leaders.

—Vassilis Angelopoulos, University of California, Los Angeles

Response

First, I would like to thank Vassilis Angelopoulos for his nomination and Lev Zelenyi, Forrest Mozer, and Masahiro Hoshino for their strong support of this nomination. I'm deeply grateful for all the things that I learned from you during different stages of my career. Working with you, I have understood how practical the good theory can be and how useful observations become being supported by reliable models. In the era of strong specialization, I was really lucky to have a chance to work with scientists ignoring boundaries between data and models, theory, and experiment. I am also truly thankful to the Macelwane Medal Committee and AGU for this distinct honor.

Starting from fully theoretical studies at the Space Research Institute in Moscow, I learned many approaches and methods from Lev Zelenyi and Anatoly Neishtadt, who have basically determined my way of thinking and working in theory. But beyond the theory, I was truly happy to collaborate with and be taught by Anatoli Petrukovich, Rumi Nakamura, and Wolfgang Baumjohann during my frequent visits to the Institut für Weltraumforschung in Graz. At that time, the extremely rich data archive of the Cluster spacecraft mission was released, giving me a chance to look on space science from a perspective that is quite new to me. Working with the magnetotail dynamics, I would never get an experience in the inner magnetosphere and solar wind physics if it were not 2 years of my postdoc research at the Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2D) in Orleans, France, with Vladimir Krasnoselskikh and Oleksiy Agapitov. Overall, my career greatly benefitted from working with many of my friends and colleagues, particularly Ivan Vasko, Didier Mourenas, Alexei Vasiliev, Dmitri Vainchtein, Andrei Runov, Xiaojia Zhang, Antonella Greco, and Gaetano Zimbardo, as well as many other colleagues with whom I was lucky to collaborate.

I am also really thankful to my colleagues at the University of California, Los Angeles (UCLA), for the wonderful atmosphere, scientific discussions, and constructive approach to many of my controversial ideas. I would like to acknowledge the Time History of Events and Macroscale Interactions during Substorms (THEMIS) team, whose work provides us with an inexhaustible set of topics for investigations. Finally, I'm deeply grateful to all the students from UCLA and the Space Research Institute with whom I had a chance to work.

—Anton Artemyev, University of California, Los Angeles

Emily V. Fischer

Citation for Emily V. Fischer

Emily Fischer is a dynamic leader in atmospheric chemistry. She is pushing the envelope of our understanding of atmospheric reactive nitrogen and is a visionary leader in efforts to bring gender diversity to atmospheric sciences.

Tropospheric ozone is not emitted but made in situ from hydrocarbons, sunlight, and oxides of nitrogen. Nitrogen oxides are usually short-lived but can be carried to distant locations via the formation of the temporary reservoir species peroxyacetyl nitrate (PAN). While we have been able to measure PAN in situ, for some time now, a global perspective was lacking. Fischer used the Tropospheric Emission Spectrometer (TES) instrument aboard the Aura satellite to develop global maps of PAN. This was an extremely challenging feat, one that was widely assumed to be impossible because of the low contrast in the infrared spectrum of PAN. Using these measurements, Fischer has evaluated model predictions of column PAN over the Atlantic and enabled quantification of summertime hemispheric transport. Fischer has an exceptional body of work on wildfires. She showed that climate change is likely to impact future human- and lightning-ignited wildfires similarly. She led the Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WE-CAN) C-130 aircraft field campaign, a National Science Foundation (NSF) program, in the summer of 2018.

Fischer is a pioneer in broadening participation from underrepresented communities in science, technology, engineering, and mathematics (STEM) fields and, in particular, that of women in geosciences. She leads research to understand how to enhance access to Earth science opportunities by women and other marginalized scientists. Her NSF-funded research project (Promoting Geoscience Research, Education and Success; PROGRESS), designed in collaboration with social scientists, is building strategies to support the persistence of undergraduate women interested in the Earth sciences. She has published extensively on this topic. Her longitudinal studies of PROGRESS cohorts demonstrated the importance of connecting undergraduate women to female role models and showed that the odds of a female undergraduate student persisting within an Earth science major approximately doubled for each female role model they identify. The role model approach in PROGRESS is patterned after the highly successful Earth Science Women's Network (ESWN), to which Professor Fischer has provided ongoing leadership. On its behalf she accepted a 2018 Presidential Award for Excellence in Science, Mathematics and Engineering Mentoring (PAESMEM) and a 2017 American Meteorological Society Special Award.

Please join me in congratulating Emily Fischer for her honor as a recipient of the James B. Macelwane Medal.

—Ronald C. Cohen, University of California, Berkeley

Response

Thank you, Ron, both for your kind words in this moment and for always teaching me something new!

This award has given me a chance to reflect on teams that I have contributed to over the past decade. Like many disciplines, atmospheric chemistry moves forward via teamwork. Ideas nurtured by teams, particularly teams including diverse perspectives and disciplines, have allowed me to see new questions that would have otherwise been invisible to me. Leading the WE-CAN team has been the ultimate challenge. Thankfully, this team is filled with some of the most competent, humble, and collaborative individuals. Frank Flocke and Bob Yokelson provided exceptional logistical mentorship. Shane Murphy and Lu Hu continue to be fantastic colleagues. I have learned so much from Vivienne Payne and her teammates at the Jet Propulsion Laboratory. They have opened my eyes to satellite observations, so much so that I dream of new missions. I would like to thank the PROGRESS team, particularly Paul Hernandez and Brittany Bloodhart, for your patience with me as I learned how to lead a social science project. Finally, I learned enormously from ESWN. This organization has had an immense impact, and I have to give credit to Yi-wen Huang for encouraging me to get involved. I also have been reflecting on my team at Colorado State University (CSU). Ilana Pollack has been the ultimate partner, ensuring the success of our ambitious field projects. I cherish my former and current students, who always impress me with their meticulousness and creativity. I would also like to thank our CSU staff for supporting all of our science. I appreciate Dave Randall, Sonia Kreidenweis, and Jeff Collett for constantly role modeling excellent leadership.

There have also been so many individuals who have influenced me. Alex Pszenny, Jack Dibb, and Bob Talbot taught me how to write. Thanks to Jennie Moody. You were the first female faculty member to mentor me; I should have thanked you sooner for showing me how to combine meteorology and chemistry. Dan Jaffe made my Ph.D. fun—thanks for setting a high bar. I would like to thank Daniel Jacob and Dan Schrag for providing some of the best scientific and career advice. I also learned so much from Jennifer Logan. Finally, there are many colleagues whom I am grateful for on a weekly basis. Thank you to Melissa Burt, Abby Swann, Rebecca Barnes, Sheryl Magzamen, and Meredith Hastings for all your energy and insights.

—Emily V. Fischer, Department of Atmospheric Science and School of Global Environmental Sustainability, Colorado State University, Fort Collins

Citation for Francis A. Macdonald

Francis A. Macdonald

Francis Macdonald is a field geologist by training who now tackles questions ranging from basin development and tectonics through to paleoenvironmental reconstructions and long-term climate change. In each of these disciplines, the impact that both he and his students have had is strikingly clear. As an undergraduate at the California Institute of Technology (Caltech) nearly 20 years ago, Francis was an author on a now classic report in *Science* showing that this rock traveled from Mars to Earth without any significant heating, demonstrating the possibility of the interplanetary transport of life. He then spent a year in Australia honing his skills as a field geologist by completing studies of several Precambrian impact craters that had been started by the late Eugene M. Shoemaker before a tragic high-velocity impact took him from us.

For his Ph.D. work Francis cracked several critical knotty problems in Neoproterozoic stratigraphy related to "snowball Earth" events that had been bothering the community for many years. In the process, he brought order to the tumultuous transition from the microbial world of the Precambrian to the familiar one of macroscopic organisms. He won acceptance for the most radical climate change hypothesis (snowball Earth), demonstrating that there were only two such events during Proterozoic time, that they were globally synchronous, that the glacial deposits in North America were indeed low latitude, and that the Sturtian snowball Earth event lasted nearly 60 million years—unprecedented in Earth history. Along with developing data constraining the timing, extent, and nature of glaciation, his more recent work has been focused on why Earth has experienced extreme climate change and what controls Earth's climate state. This work has explored the theoretical limits of albedo catastrophes and the role of changes in global weatherability and carbon dioxide sinks on Phanerozoic climate.

Francis has boundless energy and works on countless terrains, giving him a truly unique and global perspective on questions of interest. His choice of geological problems to tackle, and ability to purse them to completion, is second to none. His attention to the basic geology and detailed stratigraphic relationships and willingness to do detailed geological field maps in wild (and actually dangerous) areas have allowed him to locate the critical sections that reveal the nature of fundamental events in Earth history during one of the most environmentally exciting intervals of geological time.

Please join us in celebrating Dr. Francis A. Macdonald for his receipt of the James B. Macelwane Medal.

—Joseph Kirschvink, California Institute of Technology, South Pasadena

Response

As an undergraduate, Joe Kirschvink gave me incredible opportunities to work in his lab. He inspired me to be a scientist. I thank the Caltech Division of Geological and Planetary Sciences for their training and patience. Particularly, classes with Jason Saleeby and Brian Wernicke helped me discover field geology. I feel incredibly lucky to have stumbled upon a vocation that fits my skills and disposition so well.

After college, I was supported by the Watson Foundation to map the geology of meteorite impact structures in Australia. I used the housing budget to buy a field vehicle and immersed myself in the Outback. I thank the Watson Foundation for taking a great risk on me and for supporting young people to follow their passion. I also thank Carolyn Shoemaker for sharing Gene's work with me and bringing me into her home and family.

At Harvard, Paul Hoffman gave me freedom to explore and to fail. He supported reconnaissance trips to Alaska and Mongolia that became the core of my thesis. To this day, Paul continues to challenge me about every aspect of my work while also supporting me at every turn. Paul has been the perfect adviser for me and has developed into my favorite geology pen pal. His coupled intellectual generosity and youthful curiosity are an inspiration.

I thank Harvard's Department of Earth and Planetary Sciences for investing in me. I was blessed not only with great students, resources, and a caring chair in John Shaw but also colleagues who pushed me both in depth of rigor and breadth of relevance to fields beyond traditional geology.

Any successes I have had in geology have been due in part to great collaborators. I particularly thank Tanja Bosak, Phoebe Cohen, Jim Crowley, Galen Halverson, John Higgins, Oli Jagoutz, David Johnston, Davey Jones, Paul Karabinos, Bill McClelland, Tony Prave, Sara Pruss, Alan Rooney, Mark Schmitz, Dan Schrag, Erik Sperling, and Nick Swanson-Hysell.

My graduate and undergraduate students have inspired me to be a better teacher and mentor and have pushed my science. I thank my former graduate students, Uyanga Bold, Athena Eyster, Emmy Smith, and Justin Strauss; my current graduate students; and Lyle.

Last, I thank my family for supporting my weird rock whispering. My parents have provided a strong foundation, inspiration, and continued encouragement. Win is the greatest field assistant in the world. Kelsey and Zoe give me love and joy.

—Francis A. Macdonald, University of California, Santa Barbara

Citation for Erik van Sebille

Erik van Sebille

Erik van Sebille has quickly established himself as a world-leading scientist in applying Lagrangian techniques to study a range of oceanographic problems. His work has fundamentally advanced our understanding of ocean dynamics and the global transport of plankton and plastics. Erik is a highly creative and skilled scientist, with a knack for seeing opportunities to produce new scientific analyses to address tough problems in areas that have a direct societal impact. Erik works in a highly collaborative way, engaging with many groups and communities, applying his wares to fields ranging from oceanography through to mathematics, paleoclimate, and marine ecology.

In his research, Erik combines models and data to study how currents move tracers and particulates around the global ocean. This has resulted in high-impact papers in Lagrangian oceanography and in the ocean transport of water, heat, nutrients, microbes, plankton, and plastic around the world. With a keen eye to being an enabler of research for others, Erik has led the development of a new, cutting-edge open source software framework for Lagrangian ocean analysis, known as OceanParcels

(oceanparcels.org), which is now widely used by the community. Over the past decade Erik has rapidly broadened his work using Lagrangian techniques to track more than just water masses: exploring how ocean currents determine the fate of plastic, plankton, and other floating matter. Erik's work on plastics in the ocean has had a remarkable impact on our understanding of this global environmental problem.

Apart from being an exceptional scientist, Erik is known for his strong commitment to public outreach and community engagement. He is a regular commentator in the media, a superb teacher and communicator, and a willing mentor to research students and early-career scientists. Erik has taken on leadership roles in both national and international science programs. Erik's insights are deep, and the problems he works on are vital for protecting the world's ocean environment.

On a personal note, I have to say that it has always been a great pleasure to work with Erik. I have marveled at his energy and passion for ocean science, his flair for coming up with exciting new problems to tackle, and his ability to devise novel applications of Lagrangian methods. I am certain that we will be hearing much more about Erik's discoveries for many years to come. Please join me in congratulating Erik for this well-deserved honor of the James B. Macelwane Medal.

—Matthew H. England, University of New South Wales, Sydney, Australia

Response

Thank you, Matt, for these very kind words. And thanks to you and my other supporters and nominators for their time and efforts. I truly am very excited and humbled to receive this James B. Macelwane Medal.

I've been lucky in my career to have been surrounded by inspiring, good-natured supervisors, colleagues, and collaborators, who've shown me how much fun it can be to be an academic: Will de Ruijter, Peter Jan van Leeuwen, and Femke Vossepoel at Utrecht University encouraged and inspired me to find my own edge in research; Lisa Beal and Bill Johns at the University of Miami's Rosenstiel School of Marine and Atmospheric Science instilled a huge appreciation for oceangoing research and the hardship and effort that collecting data in the field requires; Matt England at the University of New South Wales Climate Change Research Centre has encouraged me to look beyond physical oceanography and to collaborate with biologists, geneticists, mathematicians, archaeologists, ornithologists, fisheries economists, and many other fields I've since published with; Joanna Haigh and Martin Siegler at Imperial College London's Grantham Institute have introduced me to policy and advocacy and shown me how to make a real impact; and Henk Dijkstra at Utrecht University gives me full freedom to explore and chase my own interests. Add to that all the fantastic and inspiring collaborators and coauthors (over 480 of them!), and I can really say I'm standing on the shoulders of giants. Looking back, it may seem like my career path was all nicely planned, but of course, much of this was serendipity and being in the right place at the right time. I am fully aware and appreciate that I'm privileged and realize that not everyone has access to these chances and opportunities.

Our global society is changing so fast right now that we scientists cannot simply keep doing our work like we've always done. To stay relevant, we need to change every aspect of our research: planning our research through cocreation with the broader society; conducting our research in a fully transparent, inclusive, and collaborative way; communicating our research to peers and the broader public; and getting recognized and rewarded in an unbiased way; society rightly demands radically open science. The tools and ideas for this radically open science are in place; now it's up to us as a scientific community to embrace them. These are exciting times!

—Erik van Sebille, Utrecht University, Utrecht, Netherlands

Michelle F. Thomsen Receives 2019 John Adam Fleming Medal

Michelle F. Thomsen was awarded the 2019 John Adam Fleming Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "original research and technical leadership in geomagnetism, atmospheric electricity, aeronomy, space physics, and/or related sciences."

Michelle F. Thomsen

Citation

Since the beginning of the space age, the environment outside Earth's neutral atmosphere has been a laboratory for fundamental plasma physics, for the interaction of the solar wind with the bodies of the solar system, and for phenomena that impact our daily lives. Dr. Thomsen has been at the forefront of space plasma research throughout her career. Her work blends discovery, insight, theory, and skillful data analysis. It has left its mark on our cumulative knowledge and on numerous young scientists mentored by her.

The International Sun–Earth Explorer (ISEE) spacecraft made pioneering observations of the shock formed by the supersonic solar wind encountering Earth's magnetosphere. The universality of shock waves, their implication in generating cosmic rays, and the contradiction between the collisionless nature of interplanetary space and the requirement for shock dissipation fueled intense scientific activity. Dr. Thomsen discovered the mechanisms for energy partition among electrons, ions, and suprathermal particles and their primary dependence on shock conditions. She discovered intense explosive events, known as hot flow anomalies, capable of distorting the magnetosphere. Her studies of shock particle acceleration and magnetic structure represent both the discovery and comprehensive underpinning of modern shock physics.

Dr. Thomsen exploited the Los Alamos geosynchronous data sets to reveal the dynamics of Earth's magnetosphere. She demonstrated that intense space weather events require a combination of interplanetary conditions and the state of the plasma in the magnetotail, thus linking bursty flows in the magnetotail to the intensity of geomagnetic activity. Her insight into magnetospheric flows led her to underpin the physics of the *Kp* index as a measure of activity.

Dr. Thomsen's masterful analysis of in situ plasma data led to several important studies at Saturn, including the identification of plasmoid structure in its magnetotail. This confirmed the operation of magnetic reconnection in the Saturnian magnetosphere, attributing simultaneous measurements of energetic neutrals to charge exchange with the reconnection-accelerated ions. Her expertise in the Cassini Plasma Spectrometer (CAPS) instrument led to the first discovery of cold charged nanometer-size water ice grains in the geyser plumes from the moon Enceladus. Such grains had been hypothesized to exist in a number of astrophysical contexts.

Throughout all these scientific advances, Dr. Thomsen mentored numerous students and postdocs in the art of rigorous scientific discovery. She has played active roles in community service at local and national levels. She epitomizes the qualities of scientific excellence and leadership that have led to her Fleming Medal.

—Steven J. Schwartz, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder; also at Imperial College London, London, U.K.

Response

I am deeply grateful to be receiving the Fleming medal, but I feel strongly that it should really be awarded to an entire community of space scientists. Space science, especially work based on spacecraft measurements, is not a lone-wolf operation. In my entire list of publications, only two are sole authored. The rest either have at least one (and often several) coauthor or else were first authored by someone else. In fact, the best papers were generally not mine! At last count, 155 of my colleagues have granted me the privilege of participating in their research. And I haven't counted them, but probably many more than that have contributed their expertise and insight to my own work. Some of these colleagues read like a Who's Who of space science, and others were youngsters, just setting out on the grand adventure. To all of them I am deeply grateful for the collegiality and unselfishness that has marked our journey.

I have also been greatly privileged to be able to participate in a number of groundbreaking missions, including the first spacecraft measurements of Jupiter's and Saturn's magnetospheres, the first high-resolution measurements of Earth's bow shock, the first in situ observations of a cometary coma and tail, unique plasma measurements from a six-spacecraft constellation of geosynchronous satellites, in-depth plasma and composition measurements from 8 years of Cassini's orbit around Saturn, and the rich new plasma data from Juno at Jupiter. The instruments that returned the data from these missions were a marvel of design and construction, and I am greatly indebted to all the scientists, engineers, and other support personnel whose efforts produced such great scientific opportunity. And finally, I am grateful for the encouragement and support of my wonderful family, who have made it possible for me to pursue such a richly rewarding career. I am therefore pleased to accept the Fleming Medal on behalf of the entire "village" of people who have brought us to this day.

—**Michelle F. Thomsen,** Planetary Science Institute, Tucson, Ariz.

Leigh Royden Receives 2019 Walter H. Bucher Medal

Leigh Royden was awarded the 2019 Walter H. Bucher Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "original contributions to the basic knowledge of the crust and lithosphere."

Leigh Royden

Citation

Leigh "Wiki" Royden is a leader in the study of geodynamics, where she masterfully combines physical models with geological observations. Her unique perspective, creativity, and expertise have led to a range of diverse work that has led to profound insights into tectonophysical processes based on beautifully simple and physically insightful theory. In particular, Dr. Royden made vast new inroads in the understanding of the processes that control mountain building, subduction, and continental deformation. Among her most impressive accomplishments are four main topics: the dynamics of subduction, the development of sedimentary basins, the thermal evolution of mountain belts, and the dynamics of flow in the lower crust and its relevance to the growth and structure of mountain ranges and high plateaus. As an example, the range of expressions of the slab pull force during subduction and its expression on the surface were one of the early guiding insights of Royden's scientific career. She showed how the origin of foreland basins, trench migration rates, and topographic and gravimetric signatures all depend on the force equilibrium and pressure distribution in and around subduction zones. This vision provides a completely new and original understanding of subduction process, with insightful application to and prediction of Mediterranean subduction zones. She explored the thermal evolution of mountain belts, predicting metamorphism and the dynamics of flow in the lower crust and its relevance to the growth and structure of mountain ranges and high plateaus, with application to the case of Tibet.

This masterful combination of geophysical and geological field work and theoretical analysis spurred numerous follow-up studies and a profound revision of how we think about subduction, orogeny, and, more generally, continental dynamics.

Besides her fundamental scientific contributions, Dr. Royden has also been actively engaged with the wider community by means of a number of important service commitments on a national and international level. Dr. Royden has been a champion of inclusivity and diversity within the Earth sciences for decades and has mentored numerous junior researchers, as well as engaging in direct action to address career challenge issues for female faculty.

—**Claudio Faccenna,** University of Roma Tre, Rome, Italy; also at University of Texas at Austin

Response

It is a great honor, and pleasure, to be awarded the 2019 Bucher Medal. As I write this, I anticipate that I will be on a ship in Antarctic waters during the 2019 AGU Honors Ceremony, but my mind and spirit will be very much with my assembled friends and fellow scientists. I have come to realize the great good fortune that we, geoscientists, have, that we belong to a global "village." We come from different backgrounds, nationalities, and cultures but are united in our passion for understanding the processes that shape our place in the universe, the Earth, the planets, the stars, the mountains, the origins and evolution of life itself. Together we advance this understanding through our shared work, collaboration, and friendship.

Of the many people who have been so important to my scientific life, I would like to single out three who supported and contributed to my early years as a scientist: first, my Ph.D. adviser, John Sclater, without whom I would have become a rowing coach rather than an Earth scientist—John emphasized the importance of risk taking in scientific research, with the statement "if you are never wrong, you are not sticking your neck out far enough"; second, my Massachusetts Institute of Technology (MIT) colleague and former husband, Clark Burchfiel, who taught me almost everything I know about field geology and the importance of interpreting field data within a larger tectonic context; and third, my former MIT colleague Marcia McNutt. As I watched Marcia, a few years senior to me, doing it all—professorship, tenure, children—it never occurred to me that as a woman, I could not do all these things too.

As I envision the stage containing this year's honorees, I think how wonderful to see so many women recognized for contributions to science at the highest level. A remarkable event, worthy of celebration. And yet…I look ahead to a time when this stage hosts so many women scientists that we no longer find it remarkable.

—**Leigh Royden,** Massachusetts Institute of Technology, Cambridge

▶Read more citations of and responses from recipients of AGU honors at eos.org/agu-news.

Maureen E. Raymo Receives 2019 Maurice Ewing Medal

Maureen E. Raymo was awarded the 2019 Maurice Ewing Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "significant original contributions to the ocean sciences."

Maureen E. Raymo

Citation

Maureen "Mo" Raymo's contributions to the geosciences transformed the understanding of Earth's climate on tectonic, orbital, and shorter timescales. Mo pushed the envelope in research on the marine record of orbital variability in Earth's climate over the past few millions of years and authored highly cited and inspiring papers. She did not remain within this broad topic but branched out to research linkages between climate and tectonic regimes, climate variability and oceanic geochemical cycles (including the carbon cycle), and the effects on deep-sea biota and deep-sea circulation patterns. She provided new insight into the correlation between ocean circulation and climate in SE Asia, Africa (over the time of evolution of humans), and the U.S. West—an impossibly impressive list. Her research on the interplay among ocean circulation, ice sheets, and climatic records over the initiation of Northern Hemispheric glaciation and changes in the dominant variability of glacial–interglacial climate change has inspired a large volume of research that is important for our understanding of changes in Earth's climate.

In addition to her scientific excellence, Mo has been a superb supporter of her many undergraduate and graduate students, as well as postdoctoral advisees, encouraging them to bring out the best in their research and copublishing outstanding work. She has been a major contributor to the paleoclimate research that has been used in the evaluation of anthropogenic climate change and cited in the Intergovernmental Panel on Climate Change reports. In addition, she has been a popularizer of science, as shown in the book *Written in Stone: A Geological History of the Northeastern United States,* cowritten with her father. This book is an excellent example of making science accessible to people who are interested but not professionals. This interest in making science accessible to nonprofessionals is also shown in her active involvement in public lectures on climate change, in producing web content (e.g., "How high will the waters rise?"), and in contributing to articles for the general public ("How the New Climate Denial Is Like the Old Climate Denial," February 2017, *Atlantic*).

Mo Raymo has served the paleoclimate community in many ways, including decades of service in the Ocean Drilling Programs, as well as membership in the Advisory Council of the Climate Science Legal Defense Fund. At a time when not only climate change science but science in general is under assault, it is exciting and gratifying to see that Mo Raymo, who combines excellence in research with advocacy for science, has been rewarded with the Maurice Ewing Medal.

—**Ellen Thomas,** Yale University, New Haven, Conn.; also at Wesleyan University, Middletown, Conn.

Response

Thank you, Robin; the Navy; my nominator, Ellen Thomas; and fellow AGU members. It is a wonderful honor to receive the Maurice Ewing Medal especially as, every day, I go to work in the Lamont-Doherty Core Repository, a testament to the foresight of "Doc" Ewing, who insisted that the Lamont research ships collect "a core a day." Decades later, a revolution in our understanding of Earth's natural climate variability would spring from these innocuous cylinders of deep-sea mud. I arrived at Lamont in 1982, a decade after Ewing's departure—by that time women had become a significant cohort of the graduate student body. Today, I would like to thank those gals for providing fellowship, support, and peer mentoring, before "mentoring" was even a word in our vocabulary. Thank you, Delia Oppo, Christina Ravelo, Rosanne D'Arrigo, Terry Plank, Robin Bell, Lisa Tauxe, Julia Cole, Suzanne O'Connell, Emily Klein, Carol Raymond, Kerry Hegarty, Ellen Kappel, Anne Grunow, and others. Somehow, we all thought a career as a scientist would be possible, even though there was very little physical evidence to that effect. I believe it was our critical mass that gave us confidence and strength.

Of course, I'd like to also thank my family, my partner, Ray, and especially my now grown children, Victoria and Daniel, for their unwavering love and support over the years. I'd also like to thank two organizations that never made me feel anything less than a scientist fully deserving of a seat at the table—the National Science Foundation and the International Ocean Drilling Programs. My career would not have been possible without the early support provided by these organizations. Last, I'd like to thank my colleagues at Lamont, to where I returned in 2011. It is an absolute pleasure to go to work every day and be among so many smart and inspiring people who are passionate about our planet's past, present, and future. I am truly grateful. Thank you.

—**Maureen E. Raymo,** Lamont-Doherty Earth Observatory, Columbia University, Palisades, N.Y.

S. Majid Hassanizadeh Receives 2019 Robert E. Horton Medal

S. Majid Hassanizadeh was awarded the 2019 Robert E. Horton Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "outstanding contributions to hydrology."

S. Majid Hassanizadeh

Citation

Majid Hassanizadeh has made seminal contributions to hydrological sciences through pioneering and highly impactful research in the formulation of fundamental theories for flow and transport in porous media and is most deserving of receiving this honor. With this recognition, he joins a group of world leaders and pioneers who changed the field of hydrology with lasting scientific and broad societal impacts.

Dr. Hassanizadeh, in his almost 40-year-long career, has made significant contributions to the fundamentals of porous media processes that have led to a new paradigm in modeling critical porous media–related processes in the hydrologic cycle, geologic media, and industrial systems. Early in his career, in collaboration with William Gray, he developed a rigorous and unified approach based on averaging and the principles of physics and thermodynamics, referred to as the "hybrid mixture theory" and "averaged thermodynamic approach" for basic porous media process formulation. The approach has been employed to derive new and advanced theories for non-Fickian and high-concentration dispersion and nonequilibrium capillarity and to extend Darcy's law for two-phase flow. This work identified a new macroscopic state variable for two-phase flow, called fluid–fluid specific interfacial area, which explicitly accounts for the physics of phase interfaces and allows physically based modeling of capillary effects. He also derived a theory that allows computing the distribution of fluid saturation fields as well as the spatial and temporal variations of the average interfacial area. His pioneering work has contributed some of the few new additions to theories of two-phase flow that have existed for decades. These formulations have also resulted in a vast body of research by mathematicians, experimentalists, and numerical modelers. The power of the averaged thermodynamic approach was further demonstrated through the introduction of the new concept of the "representative elementary watershed" that allows for physically based modeling of hillslope processes and channel networks.

Majid's services to the field as an editor and associate editor of leading hydrology journals, organizer of major conferences, and mentor of young researchers are unparalleled. As a scientist with a vision and a sense of service to the community, he set up the International Society for Porous Media (InterPore), dedicated to establishing porous media science as a new discipline. Majid's leading role in porous media research has earned him numerous awards and recognitions, including the Royal Medal of Honor of the Netherlands (Knight of the Order of the Netherlands Lion), which is one of the highest civilian awards.

—Tissa Illangasekare, Colorado School of Mines, Golden

Response

I am extremely honored to receive the Horton Medal. After a long journey in research and education, it is the most rewarding feeling to know that many have found value in my work. I am grateful to my nominator, Tissa Illangasekare, and supporters Mike Celia, Rien van Genuchten, and Günter Blöschl, who have followed my work closely and, most importantly, have offered their sustained support and valuable friendship.

When I was a child in Iran, I was always fascinated by natural springs, where the water seemed to appear from nowhere. Also, qanats that bring groundwater to the land surface by gravity were a mystery to me. Reading through Persian literature, one notices the precious role groundwater played in the rich Iranian history and civilization. No wonder, in pursuing advanced studies, I chose groundwater as my focus. My Ph.D. research was in obtaining generalized laws of fluid flow in porous media. Under the guidance of William Gray, I was able to develop a unified approach based on combining volume averaging and rational thermodynamics for deriving equations governing fluids flow and solute transport in porous media. This work led to a truly generalized Darcy's law for two-phase flow and a related nonequilibrium capillarity formulation. According to standard two-phase flow theory, capillary pressure is equal to the difference in individual fluid pressures, and saturation is the only state variable needed to describe the flow behavior. My work allowed me to question these long-standing assumptions. In particular, it showed that we need to include information about how fluids are distributed in the pores at a given saturation, and it naturally led to the introduction of fluid-fluid interfaces as a new state variable for fully characterizing two-phase flow. There is now overwhelming evidence that at any given saturation, fluids within pores can be distributed in many different configurations. The developed interfacial area model of two-phase flow and the nonequilibrium capillarity model have allowed us to describe complex processes in industrial porous media, such as diapers, fuel cells, and paper.

I am very aware that lifetime achievements, recognized by the Horton Medal, are not achieved by one individual. I have been blessed to have had the best people to help me realize this achievement. I am enormously grateful to my family, students, collaborators, and colleagues for their countless contributions over the years, helping me to get here. I proudly share this recognition with them while dedicating the medal itself to all Iranian scientists who, under very trying conditions, continue exploring new knowledge in many creative ways.

—S. Majid Hassanizadeh, Department of Earth Sciences, Utrecht University, Utrecht, Netherlands

Richard J. Walker Receives 2019 Harry H. Hess Medal

Richard J. Walker was awarded the 2019 Harry H. Hess Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "outstanding achievements in research on the constitution and evolution of the Earth and other planets."

Richard J. Walker

Citation

Richard J. Walker is the world leader in the field of highly siderophile (or iron-loving) element geochemistry. While this may sound rather esoteric, the impact of Walker's geochemical and cosmochemical research has changed how we look at Earth's history, both from the outside in and from the inside out. He developed the rhenium–osmium isotopic method to map—for the first time—the age and evolution of the lithospheric mantle and its domains. Using the same isotopic tool kit, he was able to elucidate the planet's late accretionary history and was among the first to demonstrate that asteroidal cores, sampled by some iron meteorites, formed very early in solar system history. He further pioneered the use of the platinum–osmium isotope system to test models of Earth's core–mantle interaction and to refine core crystallization histories of iron meteorite parent bodies. Walker's group pioneered measurements of tungsten isotope anomalies in early Earth rocks and mantle-derived magmas, demonstrating that primordial materials—formed in the first 50 million years of solar system history—astonishingly survived inside Earth for billions of years and are tapped now by mantle plumes rising from great depths. His group's most recent discovery that the amount of isotopically anomalous tungsten correlates with that of primordial helium in "hot spot" volcanoes from Hawaii and Iceland has lit the field on fire. This observation implies that primordial materials that formed the first tens of millions of years after initial accretion of the planet remain today sequestered at or near the core–mantle boundary. This research, which requires cutting-edge, high-precision isotope ratio measurements, is a game changer and may reflect diffusive exchange between the deep mantle and the core.

Rich Walker's impact goes well beyond these scientific discoveries, as he has been an excellent educator and mentor to a myriad of graduate students and postdoctoral scholars, most of whom have gone on to establish themselves in academia, thus representing the next generation of "siderophiles." Finally, he has devoted significant time, energy, and resources to the University of Maryland (his academic home for the past 30 years), where he is currently the chair of the Department of Geology. Walker has fittingly served as the core of the geochemical community at Maryland, where he has been instrumental in accreting world-class colleagues to the institution, thereby making Maryland a bright center of the geochemical and cosmochemical universe.

For these stellar achievements, we honor Richard J. Walker with the 2019 Harry H. Hess Medal of AGU.

—Alan Jay Kaufman, University of Maryland, College Park; and **Roberta L. Rudnick,** University of California, Santa Barbara

Response

I'd like to start off by thanking those persons who nominated and selected me for this great award. I am much humbled by this recognition, but I sure do appreciate it! I also want to acknowledge the contributions of numerous postdocs and students, as well as other colleagues at the University of Maryland and beyond. I am fortunate to have worked with a dazzling array of accomplished individuals over the years. All that has been accomplished in my lab has been a result of a team effort. I am not permitted enough words or time to thank everyone individually here, so I offer a blanket, heartfelt thanks!

Perhaps the real stars of this show are the siderophile elements. I am grateful to V. M. Goldschmidt for placing these elements in their own special geochemical category. Due to the difficulties associated with measuring many of these elements, they were somewhat neglected during the first few decades of "modern geochemistry." During that period, only a few brave souls, such as my early mentor John Morgan, sought to lay the critical groundwork for these elements and map out many of the applications we are pursuing today. The siderophile elements are now a fertile ground for much contemporary geochemical and cosmochemical research.

I began work on two siderophile elements, rhenium and osmium, while a postdoc in the mid-1980s. At the time, there were few data published for the associated isotope system, so exploring it seemed like a good thing to do. Studies involving the system are now quite common, and it is applied to a much wider range of problems than we ever envisioned in the 1980s. Accompanied by improvements to chemical separation techniques and mass spectrometers, my group has grown our list of favorite siderophile elements to include tungsten, ruthenium, and molybdenum. These elements are especially interesting because of their participation in short-lived radioactive decay systems and because their nucleosynthetic variability allows their use in tracing planetary genetics. The future is bright, as there is much yet to be learned from this group of elements.

To end I would like to acknowledge and especially thank my wife, Mary Horan. Much of the research I have been involved with over the decades has been supplemented by data provided by her, all the while many of our dinner conversations have strayed into discussions of arcane geochemical issues. Much of what I've accomplished would not have been possible without her contributions.

Thanks again to all!

—Richard J. Walker, University of Maryland, College Park

Eugenia Kalnay Receives 2019 Roger Revelle Medal

Eugenia Kalnay was awarded the 2019 Roger Revelle Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "outstanding contributions in atmospheric sciences, atmosphere–ocean coupling, atmosphere–land coupling, biogeochemical cycles, climate or related aspects of the Earth system."

Eugenia Kalnay

Citation

Professor Eugenia Kalnay is recognized for her exceptional contributions to numerical weather prediction; ensemble forecasting; data assimilation, including the production of global data sets for weather and climate research; and modeling the interactions between human society and the global environment.

While serving as director of the Environmental Modeling Center of the National Centers for Environmental Prediction (NCEP), she led development of their pioneering operational ensemble weather forecasting system, producing better forecasts with quantified uncertainties that are now part of everyday life. She also was lead author on the NCEP/National Center for Atmospheric Research 40-year reanalysis, the hugely influential effort to provide a consistent, accurate atmospheric history by using an up-to-date system to assimilate historical data, enabling important scientific advances in weather, climate, and environmental science.

With students and colleagues, she has worked vigorously to cross-fertilize nonlinear dynamics and meteorology, with a special focus on Kalman filters for data assimilation. Her textbook is a classic, and she has applied her techniques to such disparate problems as weather on Mars and carbon sources and sinks on Earth. She has especially sought to solve problems of societal relevance, helping develop the Human and Nature Dynamics (HANDY) model exploring interactions among economics, population dynamics, and environmental quality and showing how massive renewable energy installations could increase Saharan rainfall and vegetation.

Professor Kalnay is highly generous to students and colleagues. In 2015 she won the American Meteorological Society's Joanne Simpson Mentorship Award "for effectively mentoring many early career scientists, with her unstinting generosity of time and attention in providing advice, encouragement, leadership, and inspiration."

She was the first female Ph.D. recipient and first female faculty member in the Massachusetts Institute of Technology's (MIT) Department of Meteorology; her thesis explored the circulation of the atmosphere of Venus. She joined the University of Maryland as department chair in 1999 and is now a Distinguished University Professor, their highest faculty honor, after service with NASA, the National Oceanic and Atmospheric Administration, and the University of Oklahoma. Professor Kalnay's contributions have been recognized by numerous prestigious awards, including election to the U.S. National Academy of Engineering, American Academy of Arts and Sciences, Academia Europaea, and Argentine National Academy of Sciences.

For her broad and deep contributions to improved weather forecasting, Professor Eugenia Kalnay surely follows the tradition of Roger Revelle and thus is highly deserving of the medal in his honor.

—Richard B. Alley, Pennsylvania State University, University Park; **John M. Wallace,** University of Washington, Seattle; and **Steven C. Wofsy,** Harvard University, Cambridge, Mass.

Response

I am very humbled to receive this medal and want to express my deep gratitude to Mike Wallace, Steve Wofsy, and Richard Alley for their kind and generous citation, and to my friend and mentor Fuqing Zhang, whose recent unexpected passing has been devastating to our field and our scientific community.

I am grateful to Argentina, and to Rolando García, the meteorologist dean of the College of Sciences of the University of Buenos Aires (UBA), where I received an extremely good, and completely free education that later made me feel MIT was rather easy.

I left UBA, like many hundreds of outstanding students and professors, after the military dictatorship attacked them and the dean in "the night of the long police batons." García recommended me to Jule Charney, my amazing adviser at MIT.

Since about 40% of science students at UBA were women, I expected the more "advanced" MIT would have 50%, so I was shocked to be the first woman in meteorology. At MIT, I met lifelong friends, like Inez Fung, J. Shukla, George Philander, and Mark Cane, whom I want to thank again for being my mentors.

I was blessed to work at NASA Goddard and to learn and practice global modeling and data assimilation. Shukla was head of "climate" and I was head of "weather," and we both worked for Milt Halem, so I learned a lot about both climate and life. Then I became director of NCEP's Environmental Modeling Center, under Bill Bonner and Ron McPherson, who were very supportive when I wanted to change our methods. We introduced many improvements, like the first Variational Data Assimilation, and Ensemble Forecasting, and developed the first long Reanalysis, described in Kalnay et al., (*BAMS,* 1996) the most cited paper in all Geophysics.

After a decade at NCEP, my husband reminded me that power corrupts, so I asked McPherson if I could step down. I became a professor and the chair of the Department of Atmospheric and Oceanic Science at the University of Maryland, where I found what I really like to do: work with students and discover with them ways to improve models and data assimilation. In Motesharrei et al. (*Ecological Economics,* 2014) we developed HANDY, a groundbreaking model that bidirectionally coupled the Earth and human systems showing that overconsumption of nature and large economic inequality both lead to societal collapse. More optimistically, in Li et al. (*Science,* 2018), we showed that large-scale solar and wind energy in the Sahara could provide ~4 times the energy used by humanity while substantially increasing precipitation and vegetation in both the Sahara and Sahel.

—Eugenia Kalnay, University of Maryland, College Park

Ulrich Christensen Receives 2019 Inge Lehmann Medal

Ulrich Christensen was awarded the 2019 Inge Lehmann Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "contributions to the understanding of the structure, composition, and dynamics of the Earth's mantle and core."

Ulrich Christensen

Citation

Uli Christensen is one of the unique individuals who have contributed to both domains of core and mantle and as such is a fitting recipient of the Lehmann Medal. It is rare for an individual to have had such a level of impact in both domains of geodynamo theory and geodynamics.

Early in his career, in joint work with David Yuen, Uli was the first to determine how pressure-induced phase changes influence mantle convection, demonstrating the viability of circulation across the mantle transition zone.

With Al Hofmann in 1994 he showed how gravitational segregation of ocean crust in the deep mantle resolves isotopic patterns observed in mantle-derived rocks.

Beginning in the late 1990s, Uli has produced a whole host of results that have clarified the behavior of numerical dynamo solutions; along the way he has shown great leadership in the geomagnetism community by instigating the first dynamo benchmark exercise, and he has engaged with observationalists for the common advancement of the subject.

Of the pivotal contributions made by Uli, I will highlight a select few. Uli is the originator of the mapping of regime boundaries for convective dynamos as a function of control parameters such as the Rayleigh, Ekman, and magnetic Prandtl numbers. Further work illuminated the regime boundary between dipolar and nondipolar dynamos, attributed to be controlled by the local Rossby number.

A lasting legacy is work with J. Aubert to create a comprehensive scaling theory for the geodynamo. This showed how the velocities, heat transfer, and magnetic field strengths all scale with the convective power. This analysis was groundbreaking when it was introduced 13 years ago and remains at the very forefront of modern ideas of the geodynamo. A tremendous application of these ideas was to explain the magnetic fields of planets and stars.

Uli has become a much-sought-after keynote speaker at conferences as a result of his prominence in the subject and broad knowledge of the area. It should be mentioned that Uli has freely shared his numerical dynamo database with others so that they can carry out their own analyses. This approach has won him many friends. He is a fitting recipient of AGU's Lehmann Medal.

—**Andy Jackson,** ETH Zurich, Zurich, Switzerland

Response

Thank you, Andy, for your kind words, and thank you to all who conspired to get me this prestigious medal.

I was fortunate to be born at the right time. A law made by the German government when I was 17 provided generous support to students from low-income families, which allowed me to enter university. In the late 1970s, plate tectonics had come of age as an empirical theory, but its mechanism was not well understood. At the same time, computers became powerful enough for simulating complex nonlinear systems. Both fascinated me. My Ph.D. adviser was not an expert on either topic but was a very open-minded man. I was lucky that gave me a free hand for working on the numerical simulation of mantle convection on my own.

As a postdoc coming from the still somewhat parochial German geoscience community, Dave Yuen taught me, aside from a strong vocabulary in the English language, also the bold American way of tackling cutting-edge problems. Al Hofmann was so kind to host in his geochemistry department a guy who had not the vaguest idea about mantle isotopes. When I had mastered the fundamentals after 10 years, we published a paper together, marrying mantle convection with isotope modeling.

In the late 1990s, I looked for something to give my research a new twist. I was lucky again—realistic geodynamo modeling had just become practical. Gary Glatzmaier generously shared his code, and Peter Olson initiated me, coming from the very sticky world of mantle convection, to the airy physics of rotating magnetohydrodynamics. I also profited a lot from working with other colleagues, postdocs, and students. From Neil Ribe I learned that nice numerical models are most useful when coupled with a scaling theory that allows us to extrapolate them to the real world. Carsten Kutzner and I made the first steps toward understanding when a dynamo produces a dipole-dominated field. With Julien Aubert I tackled the question of what actually controls the strength of the magnetic field. I tried to reach for the stars with astrophysicist Ansgar Reiners by showing that the magnetic fields of planets and those of rapidly rotating low-mass stars follow the same scaling rule.

It was a great pleasure to collaborate with all these people and many more. I owe them tremendously, and without them my scientific career would certainly not have culminated in receiving the Inge Lehmann Medal.

—**Ulrich Christensen,** Max Planck Institute for Solar System Research, Göttingen, Germany

King, Pearson, and Zhang Receive 2019 Joanne Simpson Medals for Mid-Career Scientists

Penelope L. King, Anne Pearson, and Fuqing Zhang were awarded the 2019 Joanne Simpson Medals at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "significant contributions to Earth and space science by an outstanding mid-career scientist."

Penelope L. King

Citation for Penelope L. King

Dr. Penelope King received her Ph.D. in 1999 from Arizona State University and her B.Sc. in 1993 from the Australian National University (ANU). She is currently a professor at ANU. King is one of the most well-rounded Earth scientists of her time. She has made important contributions to the fields of igneous petrology, hydrothermal geochemistry, microanalysis, Martian geochemistry, and cosmochemistry.

In her early days, she laid out how A-type granites formed. She then transitioned her research into understanding volatile solubility in magmas and various minerals. She pioneered various spectroscopic and microanalytical methods to make these challenging measurements. This expertise launched a new chapter of her career to research the composition and evolution of fluids on Mars and other planetary bodies. Most recently, King completed a series of works on the role of gas–solid reactions in controlling the behavior of metals in magmatic and hydrothermal environments. This work may provide the long-sought-after solution to how copper is ultimately precipitated in many ore deposits. The evolution of her own research exemplifies the evolution of a highly creative scientist who brings together theory, modeling, field observations, experiments, and deep geologic intuition to tackle some of the most challenging problems in the Earth sciences.

In addition to her academic accomplishments, King has been a selfless contributor to the advancement of science. She has served on and chaired various committees of AGU, the Geochemical Society, the Mineralogical Society of America, and the Mineralogical Association of Canada. She served on AGU's Education Task Force in 2016 as well as leading a number of education and curricula committees in Australia and Canada. She contributed commentaries in *Elements* magazine on how to succeed in science. At her home in ANU, she championed new ways of recruiting and retaining diversity. For her efforts, she won the ANU Vice-Chancellor's Clare Burton Award for Excellence in Equity and Diversity for her selfless contributions to the university.

In summary, as a highly creative scientist and a selfless contributor to the scientific community and the public, King is the ideal role model for the next generation of scientists.

—**Cin-Ty Lee,** Rice University, Houston, Texas

Response

I am thrilled and honored to receive AGU's medal recognizing Joanne Simpson, who was an intellectual giant in atmospheric sciences. It also means a lot to me that Cin-Ty Lee—a scientist whose work I admire—spent nontrivial time putting together a nomination package. Thank you also to those who wrote letters and the volunteers on AGU awards committees.

I've been blessed throughout my career to work with many extraordinary mentors and an exceptional group of inspiring students. I'm especially grateful for unflagging support from my parents, Rod and Lib; my husband, David Lescinsky; and my children, Nettie and Katy. I'd also like to acknowledge wonderful mentorship and collegiality from Bruce Chappell, Allan White, John Holloway, Rick Hervig, Dick Henley, Darby Dyar, Roberta Rudnick, Charlotte Allen, Wayne Nesbitt, Currie Palmer, Marc Norman, Vickie Bennett, and Lesley Wyborn.

I was delighted when the citation characterized me as "highly creative" and a "well-rounded Earth scientist." Over the years, many colleagues have kindly suggested that I should specialize on one topic to be more successful. I've listened, agreed, and then gone to work on something new again! This award tells me that the windy path that I have taken might be going in the right direction!

It troubles me somewhat that being a creative and well-rounded scientist is noteworthy. Universities are places of learning where creativity is valued. It is widely acknowledged that creative, broad, and diverse approaches are essential for solving wicked problems like climate change. Yet creative and diverse science can be hard to comprehend. Neatly defined "stories" are favored by grant reviewers, journal editors, media agencies, our colleagues, and, commonly, even you and me! Additionally, we can easily identify successful people who have developed a single field or who work on topics similar to those we work on ourselves. I sometimes wonder how Leonardo da Vinci or Galileo would have coped in the 21st century—would they have been employed, received grants, published papers, given talks, or been relegated to the margins?

I am encouraged by AGU's emphasis on diversity in terms of personal characteristics and its recognition of diverse science through this award honoring Joanne Simpson. I plan to continue working hard to embrace and support diversity in our community and our science. Although the path may continue to be windy, I feel that the challenge is worthwhile as we aim to solve some of the most perplexing problems in the Earth sciences.

—**Penelope L. King,** Research School of Earth Sciences, Australian National University, Canberra

Anne Pearson

Citation for Anne Pearson

With sustained contributions of one cutting-edge study following after another, Dr. Anne Pearson has uncovered the origins of biomarkers and refined how we use them to study past oceans and ancient climate. Her often startling and always incisive findings are grounded in sharp perceptions and iron-clad reasoning. In less than 2 decades since earning her Ph.D., Dr. Anne Pearson has revolutionized biomarker studies.

Dr. Pearson achieved prominence in the paleoceanography and marine chemistry communities right out of the gate. She pioneered analyses of carbon-14 (^{14}C) ages of individual organic compounds as part of her graduate research with John Hayes and Tim Eglinton. Their work revealed a stunning spread of ^{14}C ages among marine biomarkers that reflects an interwoven timeline of biogeochemical processes and transformed the study of organic molecules in natural environments. Dr. Pearson pioneered the use of genetic tools and phylogenetic analyses to evaluate the origins of biomarkers, with findings that more often than not upended conventional interpretations and long-held beliefs. She has continued to innovate analytically, including new ways to measure stable isotopes in tiny organic particles, pigments, and large proteins.

Archaeal lipids can reveal past marine temperatures, information that is critical to paleoceanography and paleoclimate studies. While the origins of the lipid patterns that comprise this signal are hotly debated, Dr. Pearson used her novel isotopic tools to establish the source organisms are chemoautotrophic and fueled by ammonia oxidation. She has used innovative experimental studies and field samples to show the distributions of lipids used for temperature estimates are sensitive to cell growth rates and tied to the availability of nutrients in the water column.

Dr. Pearson's impact in science is matched by her generous efforts as a mentor of young scholars and her wide reach as a collaborator. Her former students and postdocs have gone on to make their own marks in institutions around the world. Her service to the community includes taking the time to pen white papers and review articles that guide the field and doing the heavy lifting to organize international meetings, such as chairing the Organic Geochemistry Gordon Research Conference.

Dr. Pearson's scientific contributions are creative and analytically fearless in equal measure. I suspect this would have appealed to Dr. Joanne Simpson, whose own pioneering career demonstrated both delight and determination within her journey of discovery. Congratulations, Ann, for this well-deserved honor, and I can't wait to see where your scientific adventures take us next.

—**Katherine Freeman,** Pennsylvania State University, University Park

Response

It is an honor and a pleasure to accept the AGU Joanne Simpson Medal for mid-career scientists. Thank you, Kate, for the generous citation and for being such a wonderful colleague and role model, and thank you to the others who supported my nomination and to our entire community for permitting me the privilege of a life spent in science. Success in research truly takes a village, and I have had the joy to work throughout my career with an extraordinary group of mentors, peers, colleagues, postdocs, and students. I receive this award not for myself, but for all the work we, as a network of like-minded individuals, have done together, and I hope more than anything else to continue to have a positive influence on the younger generation.

Seemingly trivial events, coincidences that turned out to have outsized impacts after the fact, and sheer luck all are part of my personal journey to this moment. My undergraduate research project with Professor Norman Craig introduced me to preparative chromatography. I was 18 years old and never imagined the extent to which those skills would determine the rest of my life—thank you, Norm. I randomly met a student from an oceanography program during a summer internship at Bell Labs, and she inspired me to switch from physical chemistry to oceanography—thank you, Stace Beaulieu. An article in *Applied and Environmental Microbiology* on polychlorinated biphenyls (PCBs) that my graduate school classmate Liz Kujawinski was reading just happened to be printed next to one on lipids of archaea…back in the old days of bound journals! Liz, for that and everything else along the way, a thousand thank-yous. I cannot possibly thank all the other important people in my scientific journey by name, as there are so many. Instead, I wish to remember the two we lost far too soon, John Hayes and Katrina Edwards, and to thank my family and my wife, Brook, for their unending support.

Finally, on the attribute of being fearless, I must disagree. In the words of Georgia O'Keefe, "I've been absolutely terrified every moment of my life—and I've never let it keep me from doing a single thing I wanted to do." Curiosity wins in the end.

—**Anne Pearson,** Harvard University, Cambridge, Mass.

Fuqing Zhang

Citation for Fuqing Zhang

Dr. Fuqing Zhang (1970–2019) was a university distinguished professor in theDepartment of Meteorology and Atmospheric Science and the Department of Statistics at the Pennsylvania State University. He received his doctoral degree in 2000 from North Carolina State University and was elected a Fellow of AGU in 2018. He was the founding director of the Penn State Center for Advanced Data Assimilation and Predictability Techniques.

He made major contributions to the fundamental understanding of atmospheric dynamics and predictability, and he revolutionized the analysis and prediction of hurricanes and severe storms through incorporating high-resolution radar and satellite observations into cloud-resolving state-of-the-art numerical weather prediction models with advanced ensemble-based data assimilation methodologies that have been widely adopted by the National Oceanic and Atmospheric Administration (NOAA) and other agencies and researchers around the world. He also demonstrated exceptional leadership, provided outstanding service to science and society, and provided great mentorship to junior scientists. He gave over 300 keynote or invited talks to various institutions and meetings. He served as principal investigator (PI)/co-PI for more than 50 federally funded research projects totaling well over $10 million.

He also served on numerous expert panels or advisory boards for the National Science Foundation, NASA, NOAA, the Office of Naval Research, the American Meteorological Society (AMS), and the National Academies. He organized numerous national and international conferences and workshops. He served as editor of several professional journals and was one of the three editors for the newest edition of the Encyclopedia of Atmospheric Sciences (six volumes, a total of 2,998 pages). He received numerous awards for his research and service, as exemplified by two major research awards from AMS: the 2009 Clarence Leroy Meisinger Award "for outstanding contributions to mesoscale dynamics, predictability and ensemble data assimilation" and the 2015 Banner I. Miller Award "for valuable insights into incorporating real-time airborne Doppler radar measurements via ensemble data assimilation, leading to improvements in forecasts of tropical cyclone track and intensity."

He also held various visiting appointments at various prestigious institutions, including Peking University, Nanjing University, the National Center for Atmospheric Research, the Naval Research Laboratory, NOAA's Hurricane Research Division, and École Normale Supérieure in France. More recently, he was selected as the 2015 Rossby Fellow of the International Meteorological Institute (Sweden), a Houghton Lecturer at the Massachusetts Institute of Technology during his 2015 fall sabbatical, the Nordenskjöld Lecturer at the University of Gothenburg in 2016, the 2017 Burgers Keynote Lecturer at the University of Maryland, and the Chair to lead the 2018 Gothenburg Chair Programme for Advanced Studies (Sweden). He was the recipient of the Penn State 2018 Faculty Scholar Medal in physical sciences. He passed away suddenly on 19 July 2019. The 2019 Joanne Simpson Medal serves a great purpose in honoring and remembering Dr. Fuqing Zhang.

—**Renyi Zhang,** Texas A&M University, College Station

Kuljeet Kaur Marhas Receives 2019 Devendra Lal Memorial Medal

Kuljeet Kaur Marhas was awarded the 2019 Devendra Lal Memorial Medal at the AGU Fall Meeting Honors Ceremony, held on 11 December 2019 in San Francisco, Calif. The medal is for "outstanding Earth and/or space sciences research by a scientist belonging to and working in a developing country."

Kuljeet Kaur Marhas

Citation

Kuljeet is an eminent secondary mass spectrometrist who has greatly advanced the in situ, high spatial resolution mass spectrometric technique to analyze nanometer- to micrometer-scale extraterrestrial particles to understand stellar nucleosynthesis and the solar–stellar connection. She has made fundamental contributions to the study of short-lived nuclides (^{7}Be, ^{10}Be, ^{26}Al, ^{41}Ca, and ^{60}Fe) in early forming solids as well as the study of heavy elements in presolar materials.

Kuljeet obtained her Ph.D. from the Physical Research Laboratory (PRL), India, in 2001. Later, she established the nano secondary ion mass spectrometer (NanoSIMS) laboratory at PRL, where high spatial resolution, in situ mass spectrometric techniques are used to address questions of scientific and spatial relevance for a broad range of disciplines. She has also made important contributions in other areas of stellar nucleosynthesis and analysis of sample return missions during her postdoctoral tenures. She has worked extensively with a wide suite of the early forming solar system solids (hibonites, calcium-aluminum-rich inclusions, chondrules, and samples returned from various planetary missions, viz., Apollo 15, Stardust, and Hayabusa-1) to understand the cosmochemical conditions and the chronological evolution of the early solar system.

Kuljeet's ability to work on projects that have rarely been ventured into has led to the majority of her publications. She is an ardent speaker and has given many talks in simple language motivating and exciting young students and children with new research findings in Earth and space sciences.

I wish her success in her future research.

—Anil Bhardwaj, Physical Research Laboratory, Ahmedabad, India

Response

I am deeply honored and humbled to receive the Devendra Lal Memorial Medal and the recognition from AGU. I take this opportunity to convey my deep and sincere gratitude to my mentors, collaborators, colleagues, and friends for their kind contribution toward various research programs that have been recognized and appreciated by my nominator, Professor Anil Bhardwaj, and the selection committee.

Professor D. Lal has been an inspirational, mentoring figure at many institutions across continents. It is, indeed, an honor to be associated with a distinguished scientific luminary whose contributions, mentoring, and enthusiasm for novel science were enormously addictive. He worked in a number of fields/areas with the efficiency of a pro. If I could advance science by even a few percent of his contribution, that would be a source of satisfaction and pride for me.

My heartfelt thanks to Professor J. N. Goswami, my Ph.D. supervisor at the Physical Research Laboratory, India, for introducing me to the world of heavenly bodies and setting me on the exploratory path of planetary sciences. I had no idea that I could carry on and eventually fall in love with pushing myself—trying to unravel the secrets of solar system formation. I also wish to thank Professor Peter Hoppe at Max-Planck-Institut für Chemie in Mainz, Germany, who opened a panorama of a world of the largest anomalies on the smallest (nano)scales during my postdoctoral tenure by initiating studies related to heavy-element nucleosynthesis in presolar grains. Touching stars is probably a dream of every child, and Professor Ernst Zinner provided me this opportunity by involving me with analyses of a "stardust" sample (NASA's 81P/Wild 2 cometary sample return mission) at Washington University in St. Louis. Words can never be enough to thank him for the pleasant discussions and time spent with him. Armed with the knowledge, good wishes, and caveats from the stalwarts of the field, I could set up my own laboratory in India and continue working in cosmochemistry.

Last, but not the least, I wish to thank my close-knit family for the unreserved support to help realize my ambition. I express my gratitude to the individuals who supported me and to AGU for endorsing the nomination.

Thank you, once again, for this honor.

—Kuljeet Kaur Marhas, Physical Research Laboratory, Ahmedabad, India

Reconstructing 150 Million Years of Arctic Ocean Climate

The drillship Vidar Viking, *operated by the European Consortium for Ocean Research Drilling, sits amid Arctic sea ice during the International Ocean Discovery Program's Arctic Coring Expedition in 2004. Sediment cores collected during the expedition were used in a recent study to shed light on Arctic climate over the past 150 million years. Credit: Martin Jakobsson, ECORD/IODP*

The high northern latitudes of the Arctic—seen as the canary in the coal mine for modern climate change—are warming at an outsized rate compared with elsewhere on the planet. Already, experts predict that the Arctic Ocean might be ice free during summer months in as few as 40–50 years. The trend has researchers concerned that resulting feedbacks, especially reductions in Earth's albedo as ice increasingly melts, may lead to rapid changes in the global climate.

To understand how the future could play out, scientists look back to other warm periods in Earth's history. Despite the Arctic's critical role in Earth's climate, however, data about the sea ice and climate history of the region are limited. Here *Stein* compiles a review of the existing literature on Arctic climate from the late Mesozoic era (about 150–66 million years ago) through the ongoing Cenozoic era.

In the late Mesozoic, Earth's atmosphere was characterized by much higher atmospheric greenhouse gas concentrations and much higher average temperatures than today. Then, during the past 50 million or so years, the planet experienced a dramatic long-term cooling trend, culminating in the glacial and interglacial cycles of the past 2.5 million years and the most recent ongoing interglacial period, in which rapid anthropogenic warming is occurring.

Much of the data presented in the review are from the International Ocean Discovery Program's Expedition 302, called the Arctic Coring Expedition (ACEX), which was the first scientific drilling effort in the permanently ice covered Arctic Ocean. Examining geological records from sediment cores offers insights into previous climates on Earth and helps scientists disentangle natural and human-caused effects in the modern climate. The author combines and compares grain size, marine microfossil, and biomarker data from the ACEX sediment cores with information from terrestrial climate data, other Arctic and global marine climate records, and plate tectonic reconstructions to create a history of Arctic conditions reaching back into the Cretaceous period.

The results reveal numerous periods of warming and cooling, but overall, the planet's temperature has mirrored trends in atmospheric carbon dioxide, with the transition from the warm Eocene to the cooler Miocene coinciding with a drop in carbon dioxide concentrations from above 1,500 to below 500 parts per million over a period of roughly 25 million years.

Although late Miocene climate and sea ice conditions might have been similar to those proposed to be in our near future, the rate of change in the late Miocene was very different from that of today. Whereas the ongoing change from permanent to seasonal sea ice cover in the central Arctic Ocean, strongly driven by anthropogenic forcing, is occurring over a timescale of decades, the corresponding change in the late Miocene probably occurred over thousands of years.

The author also highlights that as much as the sediment data reveal, there are gaps in the understanding of the record. A long interval in which sedimentation rates slowed to a crawl during the early Cenozoic era, for example, presents challenges to scientists analyzing the Arctic climate history during the Miocene, Oligocene, Eocene, and Paleocene epochs. The cause of this slowdown remains a mystery to researchers, which, the author notes, emphasizes the importance of securing additional sediment cores from the Arctic on future scientific drilling expeditions to help fill the holes in the timeline. (*Paleoceanography and Paleoclimatology,* https://doi.org/10.1029/2018PA003433, 2019) **—David Shultz,** *Science Writer*

Explaining the Missing Energy in Mars's Electrons

A new model could solve a Martian mystery, explaining why observations, including those from NASA's Mars Atmosphere and Volatile Evolution (MAVEN) orbiter, seem to show that electrons lose energy as they traverse the outermost region influenced by the planet, called the magnetosheath.

The electrons in this region originate mostly from the solar wind, charged particles that stream from the Sun into the solar system. Without its own internal magnetic field to shield it, only Mars's neutral atmosphere stands in the path of these particles, deflecting them around the planet like a rock deflects rushing water in a river.

This deflection forms a shock wave, or bow shock, in front of the planet, which gives any electrons that cross it a jolt of energy as they enter the magnetosheath and continue downstream toward the planet's atmosphere. But spacecraft observations have shown that electrons have less energy deeper inside the magnetosheath, as if their energy were dissipating.

Scientists previously invoked complex physics to show how this dissipation might occur as the incoming electrons reached Mars's atmosphere and collided with atmospheric atoms or molecules. However, one problem with that theory is that the Martian atmosphere is too thin for these collisions to happen frequently in the magnetosheath.

In this artist's rendering, NASA's Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft is depicted orbiting Mars and sampling energized electrons behind the Martian bow shock. Credit: NASA/Goddard/MAVEN

Schwartz et al. propose that this apparent "erosion" of energy is an illusion. They suggest that incoming electrons do not lose energy through collisions but that higher-energy electrons can escape from the magnetosheath as they rush past the planet, exiting the bow shock on its flanks, where it is weaker.

Meanwhile, electrons crossing into the bow shock along the flanks get less of an energy boost than electrons that hit the bow shock head-on, which explains the spacecraft readings that appeared to suggest that electrons deep in the magnetosheath had lost energy. The new model shows instead that the bow shock acts like a sieve, allowing highly energized electrons to escape and replacing them with less energized electrons.

The team's model, which captured all the major physical processes at play in a comparison with MAVEN data, could transform and simplify scientific understanding of the outer layer of the Martian environment. (*Geophysical Research Letters,* https://doi.org/10.1029/2019GL085037, 2019) **—Mark Zastrow,** *Science Writer*

Observational Data Validate Models of Sun's Influence on Earth

Scientists often rely on two important metrics in quantifying the amount of solar energy transmitted to Earth: total solar irradiance (TSI) and solar spectral irradiance (SSI). TSI measures the total solar power per unit area that reaches Earth's upper atmosphere across all wavelengths. SSI also measures the solar power per unit area but at discrete wavelengths within a certain range and with a certain resolution, which is determined by the instrument making the measurements.

Tracking and modeling variations in the Sun's output, which can vary significantly on timescales ranging from minutes to centuries, are crucial tasks in building a more complete understanding of Earth's climate. Recently, researchers have relied on models of TSI and SSI developed by the U.S. Naval Research Laboratory (NRL) and known as NRLTSI2 and NRLSSI2.

The most reliable way to validate model outputs is by comparing them with satellite-based measurements. Humans have been collecting such data for only about 40 years, and many gaps exist both in time and in which wavelengths satellite instruments have recorded. To fill gaps and extend the record further into the past, scientists rely on models that use historical indicators of solar activity, such as sunspot numbers and cosmogenic isotopes preserved in tree rings and ice cores.

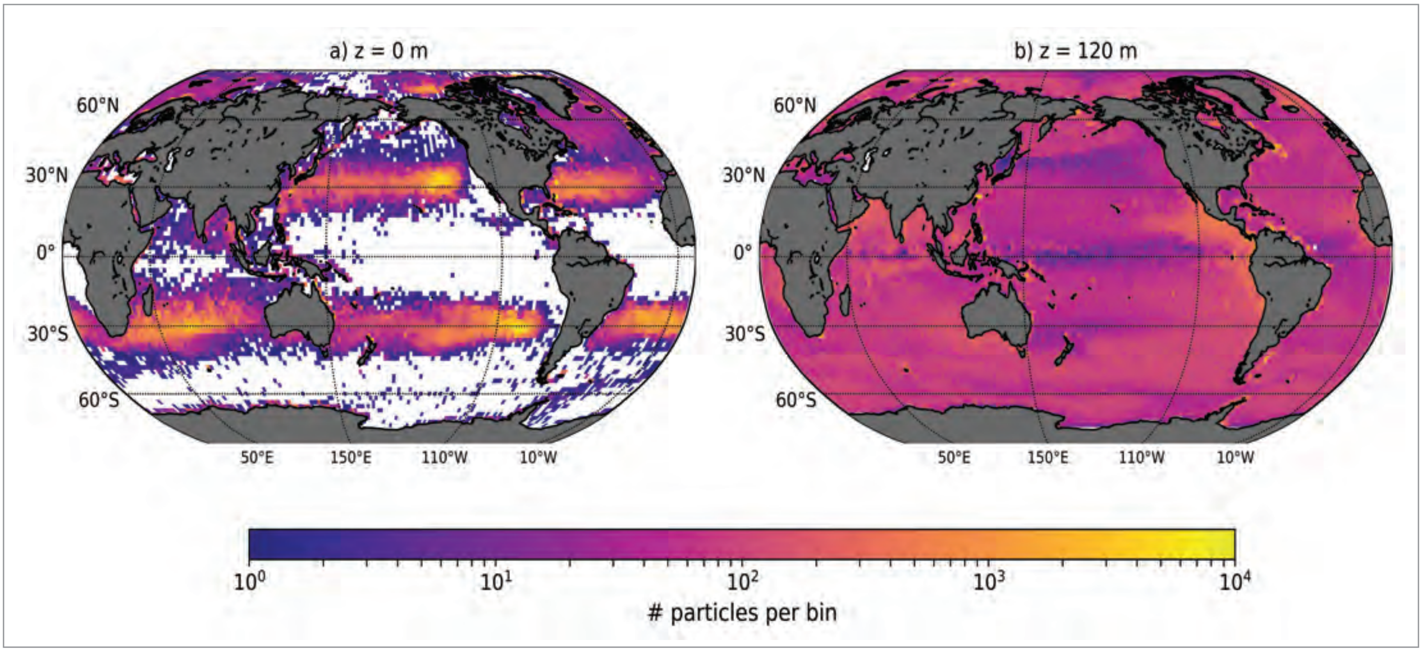
In a new study, *Coddington et al.* validate NRLTSI2 and NRLSSI2 by comparing them with independent models as well as with space-based observational data, especially from NASA's Solar Radiation and Climate Experiment (SORCE). The researchers focused on measurements of both TSI and SSI at timescales ranging from days to a decade and eventually spanning the entire era of space exploration.

They found good agreement in TSI estimates between NRLTSI2 and the SORCE data set on solar rotational timescales (roughly 1 month) as well as over a single solar cycle (about 11 years).

Validating NRLSSI2 proved more challenging. The researchers found that the model performed well over short timescales and at ultraviolet and visible wavelengths when compared with observational estimates of SSI from SORCE and other missions, including the Ozone Monitoring Instrument and the Solar Irradiance Data Exploitation SSI composite. At wavelengths above 900 nanometers, though, the team could not validate the model because of instrument noise in observational data sets. Similarly, NRLSSI2 could not be validated on solar cycle timescales because there was not enough agreement among other data sets for a comparison to be made.

The researchers highlight these gaps as areas for future study and suggest that both NRLTSI2 and NRLSSI2 are still valid tools for assessing the Sun's influence on Earth. (*Earth and Space Science,* https://doi.org/10.1029/2019EA000693, 2019) **—David Shultz,** *Science Writer*

How Are Microplastics Transported to Polar Regions?



These diagrams show modeled plastic particle concentrations in the ocean after 10 simulated years, starting from an initial uniform distribution over the entire globe. (a) At the surface, particles tend to accumulate in the subtropical gyres (garbage patches), whereas large parts of the polar regions are depleted. (b) Particles that move at a fixed depth of 120 meters do not show such accumulation zones, and high concentrations are still visible everywhere in the polar regions. Credit: David Wichmann, adapted from Wichmann et al., CC BY 4.0 (bit.ly/ccby4-0)

In recent years, the prevalence of plastics in the world's oceans has become a major environmental issue. From drinking straws and water bottles to single-use plastic bags and much smaller particles, up to 12.7 million metric tons of plastic waste are dumped into the oceans each year, with devastating consequences for seabirds and marine wildlife and potentially harmful effects on human health.

Because ocean currents can carry this waste thousands of kilometers from where it enters the water, plastic pollution has quickly become a global issue. Debris, including microplastics (particles <5 millimeters across), has been found at the poles, in sea ice, and—most visibly—in enormous sea surface garbage patches trapped by recirculating ocean gyres.

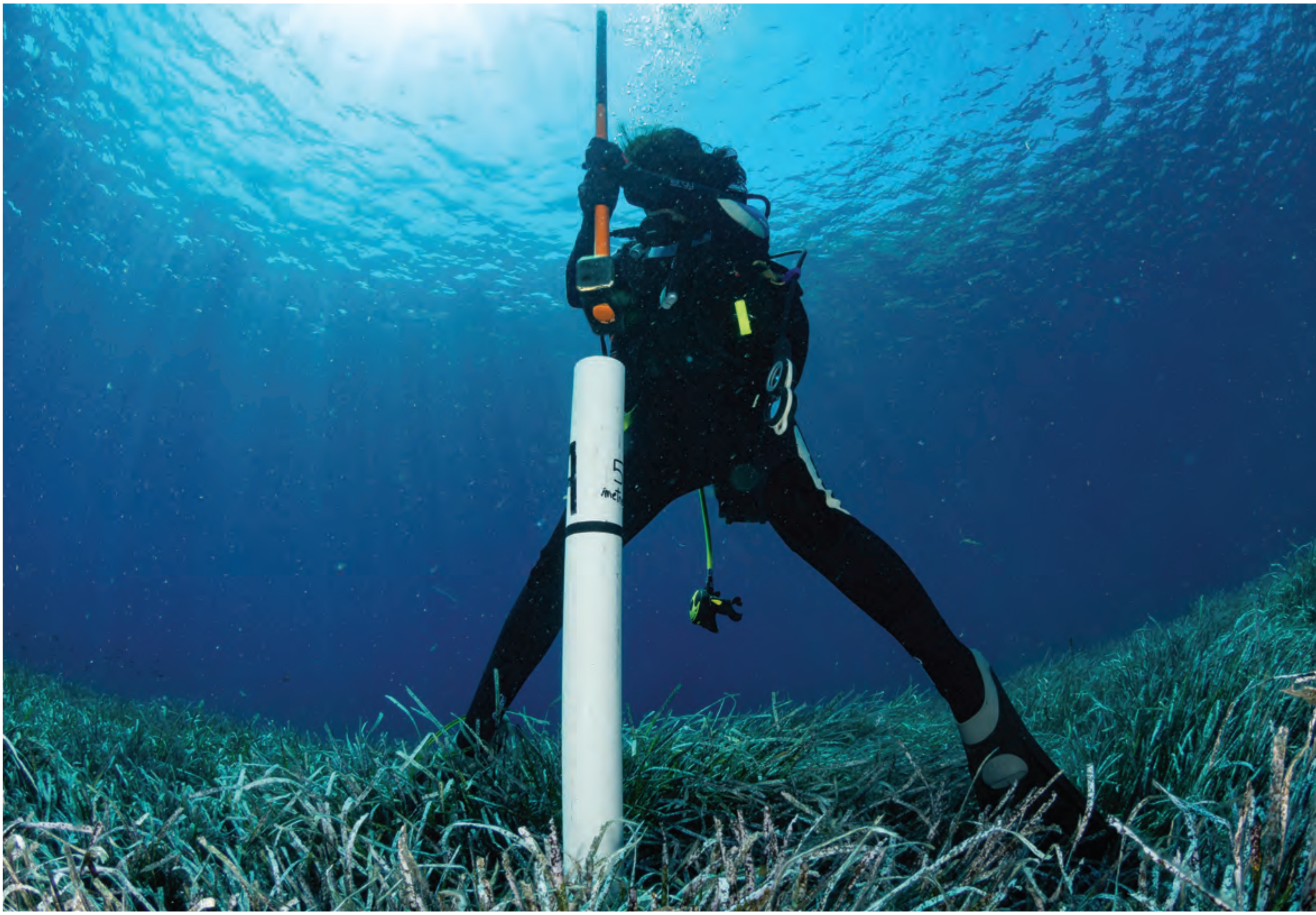
Although transport models have successfully described the distribution of microplastics observed floating on the ocean surface, these buoyant bits account for a small fraction of the total expected plastics volume. Turbulent mixing, biofouling, and a decrease in particle size appear to cause a large proportion of microplastics to sink, but what happens to these particles deeper in the water column, and whether they can account for the prevalence of plastic in the polar regions, is not yet known.

Now *Wichmann et al.* have assessed how subsurface currents disperse microplastics. Using the Parcels framework, the team modeled the trajectories of 1 million virtual microplastic particles around the globe over a 10-year period. After running the same simulations for four types of particles located at depths ranging from the surface to 120 meters, the researchers compared the resulting microplastic distributions and their transport pathways between different ocean regions.

The results indicate that submerged microplastics are controlled by different dynamics and therefore follow very different routes than particles found floating on the surface. The simulations suggest that near-surface currents carry large quantities of microplastics from subtropical and subpolar regions toward the poles—a finding that may explain why this material is commonly detected even in those remote regions.

In addition to presenting a plausible explanation for how microplastics can be transported from low latitudes to Earth's polar regions, this study offers novel insights into subsurface oceanic transport as well as the distribution of plastic particles in marine ecosystems. (*Journal of Geophysical Research: Oceans,* https://doi.org/10.1029/2019JC015328, 2019)
—Terri Cook, *Science Writer*

Improving Estimates of Coastal Carbon Sequestration



A researcher collects a soil core from a marine coastal ecosystem dominated by the seagrass Posidonia oceanica. *Data from such cores reveal how coastal vegetation like seagrass can capture and store atmospheric carbon for centuries at a time. Credit: Thanos Dailianis*

Coastal ecosystems capture large amounts of carbon from the atmosphere, sequestering it in soils for years. Estimates of how quickly this "blue carbon" accumulates influence climate predictions, but such values often suffer from uncertainties. Now *Belshe et al.* demonstrate how combining two computational modeling strategies could boost the accuracy of blue carbon estimates.

The new method builds on age-depth models, which are widely used to calculate blue carbon accumulation according to sedimentation rates gleaned from soil cores. To overcome limitations of the age-depth approach, which gives information only on the rate at which carbon accumulates, the researchers combined it with a "carbon pool" strategy. Carbon pool models—originally developed for inland settings—also estimate the age of carbon in a system and the time it remains in the system, which provides more detailed pictures of organic carbon dynamics within soils.

When applied to soil cores collected from a seagrass ecosystem in Spain's Balearic Islands, the new two-model strategy outperformed an age-depth-only approach, reducing uncertainties in blue carbon accumulation estimates.

According to the authors, the two-model approach might also generate better estimates in other coastal ecosystems, such as tidal marsh and mangrove habitats. Moreover, it could enable identification of spatial and ecological patterns in blue carbon accumulation that inform estimates in locations where extensive core sampling has not been done.

The seagrass soils sampled in this study appear to store organic carbon for centuries at a time, underscoring the potential benefits of conserving coastal ecosystems in mitigating climate change. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2019JG005233, 2019) **—Sarah Stanley,** *Science Writer*

Opposite: Brian Yurasits/Unsplash

Stored Nutrients and Climate Warming Will Feed More Algal Blooms

Lakes are full of color, their surfaces often appearing in shades of blue, gray, or brown. Some lakes, though, turn a sickly green because of large amounts of nutrients draining off of agricultural and urban landscapes.

Excess nutrients such as phosphorus can lead to nuisance algal blooms that produce toxins and deplete oxygen. As phosphorus flows into a lake, it eventually settles into the top layers of sediment. From there, it either cycles back up into the water column or is stored permanently in deeper sediment layers. Current models do not well represent the complexity of nutrient cycling processes involving sediment.

In a new study, *Markelov et al.* merged two existing models of nutrient movement in lakes. They updated the new model to account for additional chemical reactions that occur in sediments and in the water column to track nutrient concentrations over time in Lake Vansjø in Norway. They then ran simulations to determine how the lake's biogeochemistry might change under several scenarios.

Their results suggest that as the climate warms, algal blooms will worsen. The duration of annual ice cover on the lake will decrease, and prolonged wind exposure will further mix the water column. This mixing tends to shorten the length of low-oxygen periods, but algal blooms last longer and more phosphorus cycles up from the sediment.

The researchers also tested potential management options. They found that reducing phosphorus flow into the lake by half would decrease the contribution of sediment to the lake's phosphorus levels by approximately 20% in a decade. But even if phosphorus inputs were halted entirely, decreasing this contribution by 50% would take up to 200 years.

Another management tactic is to add iron to the water to bind and store phosphorus in the sediment so algae cannot use it. The researchers considered a 20-year treatment plan with this approach and found that it could be effective at Lake Vansjø, where more than half of the phosphorus present is stored in the sediment. Within a decade, dissolved phosphorus levels in this simulation dropped by nearly half, and algae biomass decreased by a third. However, once the treatment was stopped, algal biomass returned to pretreatment levels within 15 years.

The new model is an important step in evaluating treatment techniques for individual lakes, the researchers noted. Future models will have to capture algal dynamics in greater detail by including, for example, the pH of water in sediments and other factors that influence nutrient limitations. (*Journal of Geophysical Research: Biogeosciences,* https://doi.org/10.1029/2019JG005254, 2019) **—Elizabeth Thompson,** *Science Writer*

Timing Matters for Rockfall Estimates

Researchers observed this seaside cliff near the town of Whitby in the United Kingdom with lidar to determine how the monitoring interval—the amount of time between successive surveys—influences estimates of rockfall rates and volumes. Credit: Jack Williams

Rockfalls, in which gravel- to boulder-sized rocks break away from slopes, skew toward the small end on the scale of landslides. Nevertheless, they remain hazardous. Rockfalls have blocked roads, crushed infrastructure, and taken lives. Reports from around the world suggest that they may be becoming more common in response to rising temperatures in some mountainous regions, so scientists are justifiably interested in better understanding the frequency with which these geologic hazards occur.

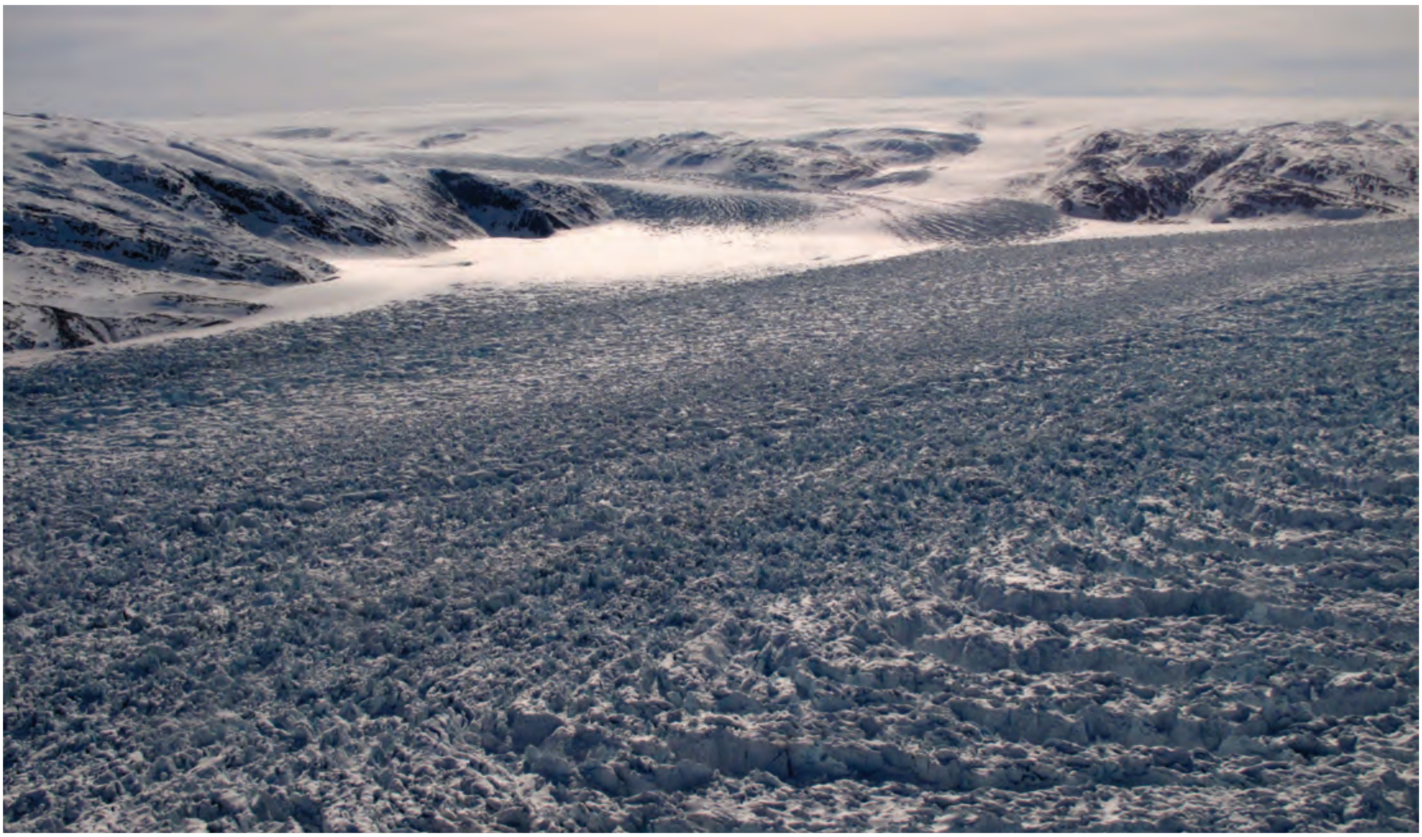
Advances in computing power and remote sensing tools, such as lidar, have allowed researchers to detect and monitor rockfalls more closely in recent years. A new study shows, however, that the monitoring interval—the amount of time between successive data collections at a site—can significantly influence estimates of rockfall rates. Researchers typically monitor for rockfalls on a monthly basis, but such long periods between surveys can lead to underestimations of small rockfalls and overestimations of large ones. This is because multiple small events can be mistaken for a single larger event when the time between surveys is longer than the return period of small rockfalls.

Williams et al. monitored a coastal cliff in the seaside town of Whitby in the United Kingdom, where Jurassic shales, sandstones, and mudstones are eroding into the sea. Here, as in most locations prone to rockfalls, the erosion follows a power law, with small rockfalls occurring more frequently than larger ones. The researchers used terrestrial lidar surveys, collected hourly over 10 months in 2015, and an algorithm to detect changes in the rock face due to rockfalls.

To find out how the monitoring interval influences rockfall rate estimates, the team modeled the frequency distribution of rockfall volumes at various intervals ranging from 1 hour to 30 days. The researchers found that changing the time interval significantly influenced the rockfall frequency and volume measured. Overall, increasing rockfall rates were seen for monitoring intervals shorter than about 12 hours, whereas for a range of intervals greater than 12 hours, observed rockfall rates were nearly identical. Specifically, the mean rockfall rate under hourly monitoring was 61 events per day—an order of magnitude larger than the six rockfalls per day seen with monthly surveys. Monitoring using the interval of 1 hour led to a threefold decrease in the average recorded rockfall volume compared with using a 30-day interval.

Given the risks posed by rockfalls of all sizes, this large increase in rockfall rate has major implications for rockfall hazard models, according to the authors. (*Journal of Geophysical Research: Earth Surface,* https://doi.org/10.1029/2019JF005225, 2019) **—Kate Wheeling,** *Science Writer*

Modeling the Subsurface Hydrology of the Greenland Ice Sheet



A new study applied the Glacier Drainage System model to Greenland's Helheim Glacier, above, to evaluate how subglacial drainage responds to different meltwater drainage patterns. Credit: Kristin Poinar

The Greenland Ice Sheet is the second-largest ice body in the world, behind the Antarctic Ice Sheet. The ice sheet spans 1.7 million square kilometers—an area roughly 3 times the size of the state of Texas—and is more than 3,000 meters thick in some places.

The Greenland Ice Sheet is also melting, which portends rising sea levels worldwide. If the entire ice sheet were to melt, scientists estimate that the global sea level could rise by 7 meters.

The ice sheet's flow is governed by complex subglacial hydrology, which influences the pace at which the ice moves toward the sea. The influence of particular sources of meltwater on the Greenland Ice Sheet's hydrology is not fully understood, adding uncertainty to predictions of future sea level rise.

In a new study, *Poinar et al.* examined how a recently discovered source of meltwater alters the hydrology beneath the Greenland Ice Sheet. The origins of this meltwater are known, but how often it reaches the ocean and whether its journey affects ice flow were not. The authors applied the Glacier Drainage System model to a large tidewater glacier in southeastern Greenland to evaluate how subglacial drainage responds to different meltwater input patterns. The research included a series of modeled experiments to test five meltwater scenarios spanning seasonal and multiyear timelines.

The authors found that drainage from firn aquifers—meltwater pockets below the surface of the ice sheet—plays an important role in forming and maintaining subglacial hydrologic systems. Firn aquifers can influence subglacial hydrology up to 40 kilometers inland, with particularly dramatic changes in the lower 20 kilometers that affect the speed of the outlet glacier. These changes occur because firn aquifers maintain subglacial channels by supplying meltwater that persists beyond the melt season and across years. As a result, the aquifers may substantially alter the seasonal behavior of glacial hydrology.

These results offer a first look at the subglacial response to meltwater supplied by firn aquifers. The authors hope that the findings will motivate new research to constrain the timing and volume of meltwater release from firn aquifers and to incorporate this meltwater into models of glacial hydrology that inform the relationships between climate, ice sheets, and sea level rise. (*Geophysical Research Letters,* https://doi.org/10.1029/2019GL082786, 2019) **—Aaron Sidder,** *Science Writer*

POSITIONS AVAILABLE

Earth and Space Science Informatics

Associate or Full (Tenured) Professor–Glaciology. The Department of Earth Sciences at Dartmouth College seeks an outstanding candidate in the area of ice-sheet dynamics to be the inaugural holder of the endowed Evans Family Professorship. This position is part of a new interdisciplinary cluster at Dartmouth focused on "Arctic Engineering in a Period of Climate Change" involving the Department of Earth Sciences and the Thayer School of Engineering. We encourage applications from candidates who use models of ice-sheet dynamics to complement Dartmouth's existing strengths in understanding glacier and ice-sheet fluctuations in the context of geological, geophysical and climatic data on multiple timescales, and experimental and theoretical ice rheology.

Particular attention will be given to candidates whose research incorporates fundamental physical processes and data analytics. The successful candidate will complement and contribute to Dartmouth's established research efforts in cold regions science and ongoing research activities in the Department of Earth Sciences and the Thayer School of Engineering. Candidates are also encouraged to explore possible synergies with other Dartmouth departments including, for example, Computer Science, Mathematics, Geography, and Environmental Studies. Additionally, there are potential collaboration opportunities with the Institute for Arctic Studies at Dartmouth, the Arthur L. Irving Institute for Energy and Society, and the nearby U.S. Army's Cold Regions Research and Engineering Laboratory. Dartmouth is part of the University of the Arctic.

The successful candidate will exemplify Dartmouth's commitment to excellence in undergraduate and graduate teaching and research. Teaching responsibilities consist of three courses spread over three of four ten-week terms. To create an atmosphere supportive of research, Dartmouth College offers faculty members grants for research-related expenses, a quarter of sabbatical leave for each three academic years in residence, and flexible scheduling of teaching responsibilities. The Department of Earth Sciences is home to 12 tenured and tenure-track faculty members in the School of Arts and Sciences, and enjoys strong Ph.D. and M.S. programs and outstanding undergraduate majors.

Dartmouth is highly committed to fostering a diverse and inclusive population of students, faculty, and staff. We are especially interested in applicants who are able to work effectively with students, faculty, and staff from all backgrounds, including but not limited to: racial and ethnic minorities, women, individuals who identify with LGBTQ+ communities, individuals with disabilities, individuals from lower income backgrounds, and/or first generation college graduates. Applicants should state in their cover letter how their teaching, research, service, and/or life experiences prepare them to advance Dartmouth's commitments to diversity, equity, and inclusion.

To submit an application, upload a cover letter, curriculum vitae, statements of teaching and research interests and objectives, reprints or preprints of up to three of your most significant publications, and the name, address (including street address), e-mail address and fax/phone numbers of at least three references to: http://apply.interfolio.com/72655 or send all documents as email attachments to earth.sciences@dartmouth.edu (attention: Glaciology Search Committee). Application review will begin February 1, 2020, and continue until the position is filled.

Dartmouth College is an equal opportunity/affirmative action employer with a strong commitment to diversity and inclusion. We prohibit discrimination on the basis of race, color, religion, sex, age, national origin, sexual orientation, gender identity or expression, disability, veteran status, marital status, or any other legally protected status. Applications by members of all underrepresented groups are encouraged.

Your offer is contingent upon your consent to a pre-employment background check with results acceptable under Dartmouth policy.

https://www.dartmouth.edu/~hrs/pdfs/background_check_policy.pdf

Interdisciplinary

Staff Scientists at Carnegie Institution for Science. The Carnegie Institution for Science (Washington Campus) invites applications for two staff scientist positions, one in petrology or geo/cosmochemistry and the second in astronomy or planetary science. For the first position, we seek candidates in research areas that will amplify our strengths in field and laboratory-based investigations, with an emphasis in igneous petrology, magmatic volatiles, or geo/cosmochemical approaches to investigate the origin and evolution of Earth and other rocky planets. For the second position, we seek candidates with research emphases in laboratory experiment, theory, or observation of planet formation or (exo)planetary atmospheres. For both positions, we encourage applications from those interested in cross-disciplinary areas that complement or expand our existing strengths in Earth, planetary, and exoplanet science. We are committed to enhancing the diversity of our staff and welcome applications from individuals with a diverse set of experiences, backgrounds, and perspective.

The Carnegie Institution is a basic research organization committed to exploring intriguing scientific questions. Carnegie staff scientists hold 12-month salaried appointments and pursue independent research supported by a combination of endowment and federal funds. Staff scientists do not have teaching duties, but we place considerable emphasis on mentoring postdoctoral scholars.

Carnegie's Department of Terrestrial Magnetism and Geophysical Laboratory are merging and will continue to provide staff scientists with the resources to pursue fundamental research on planet formation and evolution, including state-of-the-art experimental and analytical laboratories, computer clusters, and machine shop and electronics support. Information about our current research programs can be found at http://dtm.carnegiescience.edu/research and https://gl.carnegiescience.edu/our-research. Our vision for interdisciplinary planetary research can be found at https://planets.carnegiescience.edu/. Applicants should have a Ph.D. or equivalent degree and propose a world-class research program.

To apply, please submit (1) cover letter with the names of three references, (2) curriculum vitae, (3) list of publications, (4) abstracts of your two most relevant and important papers, (5) a 2-3 page summary of previous research, and (6) a research plan of up to 5 pages through the appropriate Staff Scientist application link at https://jobs.carnegiescience.edu/jobs/bbr. You may email staffposition@carnegiescience.edu with any questions.

Review of applications will begin immediately with a deadline of 18 February 2020.

The Carnegie Institution is an equal opportunity employer. All qualified applicants will receive consideration for employment and will not be discriminated against on the basis of gender, race/ethnicity, protected veteran status, disability, or other protected group status.

Visiting Faculty Position–Volcanology and Geothermal Sciences–Kyoto University, Japan. Kyoto University invites applications for a visiting Professor or Associate

Professor in volcanology, geothermal sciences and related disciplines. The successful applicant is expected to work at Aso Volcanological Laboratory or Beppu Geothermal Research Laboratory, Kyushu, Japan. Attractive salary and traveling expenses are provided from the university.

The position is opened on October 1, 2020, and the tenure is 3 to 12 months by September 30, 2021. For the details, please visit http://www.vgs.kyoto-u.ac.jp/igse/e-visiting_faculty_position.html.

Send (1) CV including publication list, (2) statement of research interests, (3) pdf files of 3 significant publications, (4) names and e-mail addresses of three references and (5) desired arrival and departure date, and place of assignment (Beppu or Aso) to Prof. Takahiro Ohkura through e-mail to VFP20@aso.vgs.kyoto-u.ac.jp by March 10, 2020.

Inquire in advance to a member of Aso or Beppu is encouraged

PhD fellowships in Andesite volcanology and geochemistry. Up to 8 Ph.D. fellowship opportunities are available to work on understanding andesitic magma systems as part of the multi-national, interdisciplinary research project Transitioning Taranaki to a Volcanic Future.

We seek motivated individuals with a background in Earth sciences and a strong academic record to participate in a collaborative, international 5-year research program. Research projects will utilize geochemistry, experimental petrology, geochemical modeling and novel technique development–in conjunction with fundamental geological techniques–to investigate the origin, evolution, and behavioral modification of eruptive processes at Mt. Taranaki Volcano, New Zealand.

Research opportunities are available on, but not limited to, the following topics:

- Experimental petrology of low-pressure crystallization to investigate timescales of magma emplacement and volatile exsolution-driven ascent and eruption.
- Isotope and trace element crystal chemical stratigraphy to quantify eruption triggering mechanisms.
- Melt Inclusion geochemistry and rheology constraints on shallow magma ascent, crystallization and degassing conduit processes during eruption.
- Understanding the role and volcanic-diagnostic possibilities of non-traditional metal volatile studies (Sn, Cu and Zn).
- Tracing magma residence times and ascent rates of Taranaki and White Island (New Zealand) volcanic using U-series and other short-lived isotope systems.
- Contrasting geochemical tracers of eruption behavior during cycles of sustained and infrequent activity using a detailed 30 ka tephra record.

The successful applicants will be awarded a full Doctoral scholarship. At the UoA current Doctoral Scholarships are $29k/a (non taxable) + tuition fees for a 3-year period. Doctoral stipends, tuition waivers, and benefits may begin as early as February of 2020, but we will also consider start dates over the next 1-2 years. Projects will be mainly hosted in the School of Environment, University of Auckland, New Zealand, but other options are available via University of Otago(NZ) University of Canterbury (NZ), Massey University (NZ) or Macquarie University Australia.

Prospective applicants are encouraged to reach out to Science Leads Dr. Ingrid Ukstins and Dr. Marco Brenna (ingrid-peate@uiowa.edu; marco.brenna@otago.ac.nz) to discuss specific research interests. Please include a CV and specify a project topic in your statement of interest.

Applications will be considered as submitted.

Scientist, Polar Ocean and Sea Ice Research. The Jet Propulsion Laboratory, California Institute of Technology invites applications for a Scientist who will bring new expertise to and ensure continuity of existing capabilities at JPL in polar ocean and sea ice observation from space. The successful candidate will lead new PI-driven research activities and will provide science support for upcoming NISAR, SWOT, and Jason missions. Specifically, the candidate will establish a research program that uses satellite data to derive new datasets of polar ocean dynamic topography, mesoscale eddies, and sea ice motion to better understand polar ocean dynamics and ocean-atmosphere-sea-ice interactions.

Qualifications:

- PhD in Oceanography, Earth Sciences, or related scientific discipline.
- Demonstrated expertise in polar-ocean and sea-ice processes, as evidenced by a publication record in the peer reviewed journals.
- Demonstrated expertise in radar altimetry for polar oceans.
- Excellent oral and written communications skills.

The following qualifications are preferred:

- Two years of related experience.
- Demonstrated technical proficiency in the development of novel datasets from satellite data for polar oceans.

ASSISTANT/ASSOCIATE/FULL PROFESSORS-GEOPHYSICS, STRUCTURE GEOLOGY, GEODESY, SPACE PHYSICS

The Department of Earth and Space Sciences(ESS) at Southern University of Science and Technology of China (SUSTech) invites applications for tenure-track (or tenured) faculty positions at the ranks of **Assistant, Associate, and Full Professors.** Applicants must have earned a doctoral degree in Geophysics, Structure Geology, Geodesy, Space Physics, Planetary Science or closely related fields. Successful applicants will be expected to establish a robust, externally funded research program and demonstrate strong commitment to undergraduate and graduate teaching, student mentoring, and professional services. These positions will remain open until filled. For more other information about ESS, please go to the website **http://ess.sustech.edu.cn/.**

SUSTech is a public university founded in Shenzhen, China. It is intended to be a top-tier international university that excels in interdisciplinary research, nurturing innovative talents and delivering new knowledge to the world. SUSTech was born in 2011 with a mission to reform higher education in China. Since then, it has been widely regarded as a pioneer and innovator in collectively moving China's higher education forward to match China's ever-growing role in the international arena. Research, Innovation and Entrepreneurship are the three pillars for SUSTech to stand out with distinctive Characteristics.

To apply, please submit an e-mail application that includes a cover letter, a CV with a full list of publications, a research statement, a teaching statement and contact information for three references to Prof. Xiaofei Chen at **chenxf@sustech.edu.cn.**

• Demonstrated community leadership through convening of scientific meetings and topical sessions, leadership roles in discipline related organizations and editorial duties.

Complete applications will include a cover letter describing the applicant's vision for their role at JPL as a leader and contributor of polar ocean and sea ice research, a curriculum vita including a bibliography of refereed and other work, a statement on research experience and research objectives, and contact information for at least three professional references. Applications received by January 31, 2020 will receive full consideration.

******IMPORTANT******

This position, because of its associated job duties, has been determined by JPL to be safety-sensitive as defined in JPL's Drug Free Workplace Requirement. An employee holding this position will be subject to periodic, unannounced, random drug testing. Please refer to JPL's Drug Free Workplace Requirement for more information. Candidates who are hired into designated safety-sensitive positions will be included in a pool from which individuals are randomly selected to participate in the unannounced drug testing.

#LI-CC1 We are an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability status, protected veteran status, or any other characteristic protected by law. JPL is a VEVRAA Federal Contractor. For more information about "EEO is the Law" click here: http://www.eeoc.gov/employers/upload/eeoc_self_print_poster.pdf

The Jet Propulsion Laboratory is a federal facility. Due to rules imposed by NASA, JPL will not accept applications from citizens of designated countries or those born in a designated country unless they are Legal Permanent Residents of the U.S or have other protected status under 8 U.S.C. 1324b(a)(3). The Designated Countries List is available at https://www.nasa.gov/sites/default/files/atoms/files/designated_country_list_8-16-2019_tagged_0.pdf

Graduate Student Research and Teaching Assistantships in Env., Earth & Atmo. Science at Umass Lowell. The Department of Environmental, Earth, and Atmospheric Sciences (EEAS) at the University of Massachusetts Lowell (www.uml.edu/sciences/eeas) offers several graduate research and teaching assistantships for motivated students for the Fall 2020 semester. Several positions are currently open, including in Glacial History of Antarctica and New England; Atmospheric and Climate Science; Geochronology and Isotope Geochemistry; Hydrogeology, and Mercury Cycling. Information about the positions can be found on our webpage.

The University of Massachusetts Lowell (also known as UMass Lowell) is an urban public research university in Lowell, Massachusetts, with nearly 1,150 faculty members and 18,058 students. EEAS offers unique interdisciplinary study programs encompassing Geosciences, Meteorology, Hydrology, and Environmental Chemistry. EEAS offers undergraduate and graduate degrees in Environmental Sciences, with concentrations in Environmental Studies, Geosciences, and Atmospheric Sciences. Graduate School admission policies are found under https://www.uml.edu/grad/.

Applications can be emailed to Erica Gavin: erica_gavin@uml.edu.

Ocean Sciences

Assistant or Associate Professor of Ocean Engineering. The Division of Marine Science (DMS) in the School of Ocean Science and Engineering (SOSE) at The University of Southern Mississippi (USM) invites qualified applicants for a full-time, 9-month, tenure-track faculty position in Ocean Engineering at the assistant or associate professor level to begin in Fall 2020. The successful candidate will be expected to contribute to the continued development of the undergraduate Ocean Engineering program, which started in 2017, and lead its ABET accreditation. Moreover, the candidate is expected to develop a strong, externally funded research program, publish in peer-reviewed literature, mentor students, participate in undergraduate instruction and develop courses in their area of study. The candidate should demonstrate the potential to contribute across disciplines and promote the continued interdisciplinary growth of the academic and research programs within the SOSE. Applicants must hold a Ph.D. in engineering or a related field and have demonstrated research experience related to the ocean. The preferred candidate has post-doctoral research experience, has participated in an ABET accreditation process, has experience in managing an established research group, and has a demonstrated record of scholarship, service, grant development, communication, and commitment to diversity. The successful candidate will be required to pass a NASA background security check and a USM employment background check.

Applications must be submitted through the jobs.usm.edu candidate portal: https://usm.csod.com/ats/careersite/JobDetails.aspx?id=1247. For questions regarding this position, contact the chair of the search committee by email: maarten.buijsman@usm.edu.

The SOSE includes two academic divisions, Marine Science, and Coastal Sciences, and several R&D centers including: Hydrographic Science Research Center, Marine Research Center, and Thad Cochran Marine Aquaculture Center. DMS is based at the NASA Stennis Space Center, which is a "federal city" that boasts the world's largest concentration of oceanographers and hydrographers. Marine Science faculty benefit from close working relationships with a number of on-site federal agencies, including the Naval Research Laboratory-Stennis Space Center, the Naval Oceanographic Office, the Naval Meteorology and Oceanography Command, the USGS and NOAA, including the National Data Buoy Center, and the National Centers for Environmental Information.

Marine Science graduate and undergraduate programs extend across traditional marine science emphasis areas in biological, physical, chemical and geological oceanography, as well as hydrographic science and undergraduate ocean engineering. Marine Science faculty and graduate programs are housed at Stennis Space Center, where the M.S. and Ph.D. degrees in Marine Science and the M.S. degree in Hydrographic Science are delivered. The Marine Science and Ocean Engineering B.S. degree programs are delivered at the USM Gulf Coast Campus in Long Beach, MS as well as at USM's main campus in Hattiesburg, MS. The Long Beach campus is near the Port of Gulfport, which is the home port for USM's R/V Point Sur and the recently opened USM Marine Research Center, which features a state-of-the-art fabrication lab, testing tank, and laboratory space. Gulfport will be the future home port of a new 199-ft UNOLS Regional Class Research Vessel, which will be managed by a USM-lead consortium.

USM is an Affirmative Action/Equal Employment Opportunity employer/Americans with Disabilities Act institution.

SEA-GOING CLUSTER HIRE

The **College of Earth, Ocean, and Atmospheric Sciences at Oregon State University** invites applications for four (4) research-focused, tenure-track, open rank professor positions who maintain or may develop vigorous, externally funded, sea-going research programs.

These positions promote interdisciplinary research across four focus areas: **Biological Oceanography, Chemical Oceanography, Physical Oceanography,** and **Marine Geology and Geophysics.**

Additional information and application procedures are available at **ceoas.oregonstate.edu/cluster-hire/**

Review of applications:
March 9-March 31, 2020.

Oregon State University

Dear AGU:

I've never done research quite as interdisciplinary as this. I'm working with archaeologist April Watson in South Florida to understand how barrier island development influenced human habitation of the islands thousands of years ago. The artifacts inform us about human activity and the sediment tells us about the environment of the time.

Digging up bones, shells, pottery, and sand in Florida during the summer makes for long, hot, humid days, but I wouldn't trade a minute of it for anything! Pictured are (clockwise from left) Alanna Lecher, Henna Bhramdat, Micheline Hilpert, and April Watson.

—**Alanna Lecher,** Lynn University, Boca Raton, Fla.

View more postcards at bit.ly/Eos-postcard