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Eos

SCIENCE NEWS BY AGU

Zhurong on Mars

Antarctica's Newfound Lake

Wetlands as a Climate Solution

ANNUAL SPECIAL EDITION

The Career Issue

Learn how 16 scientists found a track to rewarding professions.

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OK, But Explain "Anything"

One of the reasons I went to law school (I know, this is a science magazine—stay with me a second) is because when I was young, people would always say, "You can do anything with a law degree!" But nearly everyone I met during school and shortly after graduation was an attorney at a law firm. It took many years of life experience to find alternative routes to better-suited careers in which my education would still be useful.

Last year, *Eos* published its first Career Issue. It was a project that manifested from the many conversations we had with geoscientists about the same conundrum. Students and early-career researchers sometimes only have colleagues who are academics—a rewarding career for many, but it's not for everyone. Sometimes it's not even for academics over the course of their entire professional lives. So how do you know what options you have? How else can you take this wonderous knowledge of Earth and space sciences and find the career that's most rewarding for you personally?

One of the many joys of journalism is constantly seeking out and meeting a wide spectrum of people doing all sorts of jobs, projects, and tasks we may never have thought about before. That means *Eos* is in a perfect position to show off the many paths where a geoscience education can take you. We received such a good response to our first Career Issue that we're making it an annual special edition.

Inside you'll find 16 profiles of science professionals from around the world who are using their hard-earned education in all sorts of fields—yes, including academia. Some of these names you might recognize from *Eos* reporting over the past year. (Heads up: If we call you up to talk about some research and you've got an unusual job, we might just be calling you back to ask, "Hang on, how did you get there?")

Read on to learn how Michael Kotutwa Johnson uses his Ph.D. in natural resources to keep Indigenous agricultural practices alive. Jimena Díaz Leiva returned to Peru after her doctoral work in California equipped with the education and cultural knowledge to address the "really complex historical and political processes" around the country's gold mining industry. Alexandre Martinez is using his love of cool tech to bring climate education to the public through virtual reality. And community college professor Sian Procter piloted her geoscience education right up into orbit with SpaceX.

We hope you're impressed by these creative and hardworking scientists and inspired to look around for a profession that brings you joy—or if you're already there, look around and see who might like to have a guide.

Heather Goss, Editor in Chief

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Randy Fiser, Executive Director/CEO

Features

On the Cover

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Columns

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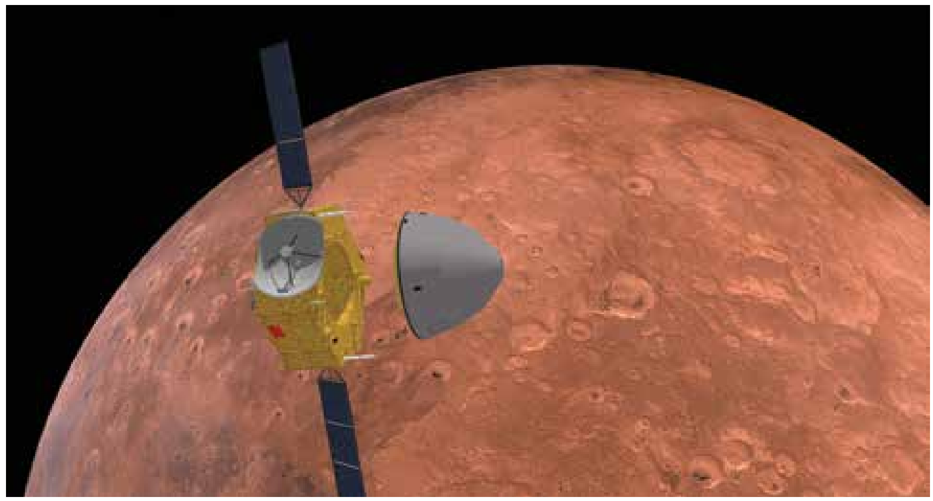
Zhurong Rover Spots Evidence of Recent Liquid Water on Mars

Mars is hardly a verdant world today, yet evidence abounds that liquid water once flowed over the Red Planet. Now, the latest rover to arrive on Mars's surface—Zhurong, part of China's Tianwen-1 mission—has spotted hydrated minerals that point to liquid water having persisted well into the Red Planet's most recent geologic period. These results, published in *Science Advances,* contribute to our understanding of when liquid water flowed on Mars, the research team has suggested (bit.ly/Mars-liquid).



China's Tianwen-1 mission has found evidence that liquid water persisted on Mars until much more recently than previously believed. Credit: Axel Monse/Shutterstock

A Close Look at Martian Plains

Just over a year ago, Zhurong (named for the Chinese god of fire) touched down in Mars's northern hemispheric lowlands. Since then, it has been sampling the morphology and mineralogy of Utopia Planitia, the same wide, sandy plain where NASA's Viking 2 lander arrived in 1976.

Yang Liu, a planetary scientist and member of the Tianwen-1 team at the National Space Science Center, Chinese Academy of Sciences, in Beijing, and his colleagues focused on spectral observations made by the rover's Mars Surface Composition Detector, an instrument designed to analyze minerals and identify sediments. They analyzed some of the data from four roughly fist-sized pieces of sediment that Zhurong passed as it traveled southward.

"We have plenty of evidence of liquid water on Mars before the Amazonian, but since approximately 3 billion years ago, the evidence for liquid water on the surface of Mars is scarce at best."

To determine the types of minerals present within the sediments, the team turned to a technique known as reflectance spectroscopy: When sunlight strikes something, certain wavelengths of light—those that set a substance's chemical bonds vibrating—are preferentially absorbed. The light reflected back is accordingly diminished at particular wavelengths, and a spectrum reveals that, said Liu. "At those wavelengths, there will be a dip [in the reflected light]."

The researchers found absorption features in the sediments' spectra in the near-infrared part of the electromagnetic spectrum at wavelengths of roughly 1.5, 2.0, and 2.2 micrometers. Those spectral fingerprints are characteristic of so-called hydrated minerals, substances like olivine, pyroxene, and feldspar that were altered as they incorporated water into their chemical structures.

Water in the Amazonian

The presence of hydrated minerals implied that liquid water once persisted on Mars, which is not a surprise because surface features like river channels and deltas have been spotted on the Red Planet. But what was unexpected was finding those minerals in terrain just a few hundred million years old. There hasn't been much evidence for liquid water on Mars during the current geologic epoch, the Amazonian, said Alberto Fairén, an astrobiologist at the Center for Astrobiology in Madrid, Spain, and Cornell University in Ithaca, N.Y., who was not involved in the research. "We have plenty of evidence of liquid water on Mars before the Amazonian, but since approximately 3 billion years ago, the evidence for liquid water on the surface of Mars is scarce at best."

Liu and his colleagues believe that the sediments Zhurong spotted are examples of Martian duricrust, a layered material that forms when groundwater evaporates and leaves behind saltlike compounds that in turn cement Mars's regolith. Duricrust has been found elsewhere on Mars, but the sediments near Zhurong appear to be particularly robust. "The duricrust at the Zhurong landing site is much thicker than that at other landing sites, suggesting much stronger water activity," said Liu.

Although it will be exciting to look for more evidence that liquid water existed in Mars's not-so-distant past, said Liu, the Tianwen-1 team might have to be patient. Mars's northern hemisphere is currently entering winter, and the combination of decreased light intensity and increased levels of airborne dust is creating challenging conditions for the solar-powered Zhurong rover. To wait out circumstances, the rover is designed to enter a sleep mode, which it may do in the coming months, the China National Space Administration recently posted on WeChat.

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

Massive Groundwater Systems Lie Beneath Antarctic Ice

If we want to understand the impacts of a warming planet, we must first learn how its coldest regions are faring. Melting ice leads to sea level rise, but our understanding of the properties of ice sheets and the ways ice streams transport fast flowing ice and sediment from ice sheets to ocean basins has been incomplete.

Now, researchers led by Chloe Gustafson, a geophysicist and postdoctoral researcher at Scripps Institution of Oceanography, have confirmed scientific suspicions, uncovering significant groundwater amid sediment below ice sheets in Whillans Ice Stream in Antarctica.

"It's this missing process that hasn't been considered in our conceptual models of how ice streams work," Gustafson said of the study, which was published in *Science* (bit.ly/groundwater-Antarctica). Scientists aren't yet sure how these groundwater systems will affect the ice sheets above them, but they represent a new and potentially weighty factor in modeling the behavior of ice sheets.

The groundwater "has potential to shape how the ice sheets evolve dramatically," said Stanford glaciologist Dustin Schroeder, who was not involved with the study. "If we want numbers we can be confident in…for sea level rise contributions from ice sheets, we have to get this component right."

"If we want numbers we can be confident in…for sea level rise contributions from ice sheets, we have to get this component right."

Although ice streams cover a tiny percentage of Antarctica, they're responsible for most ice flow from the continent's interior to the ocean. Whillans Ice Stream moves ice about 2 meters per day; other nearby streams, which range from hundreds to thousands of kilometers in length, move ice faster.

Looking Deeper Beneath the Ice

Gustafson and her collaborators observed groundwater and sediment using magnetotellurics (MT), a method that harnesses natural variations in Earth's electromagnetic fields to map subsurface properties, similar to how an MRI (magnetic resonance imaging) details the inner workings of the human body. They also gathered passive seismic data to confirm and supplement MT findings.

Magnetotelluric stations detected sediments and groundwater beneath Whillans Ice Stream in Antarctica. Credit: Kerry Key

Past research focused on shallow hydrologic systems, using techniques such as drilling through the ice to sample sediments below it, right where ice meets earth. Current models that predict the flow of ice streams include a film of water just millimeters thick atop a much thicker layer of sediment, or till. In the past, modelers believed the till sat atop an impermeable layer of bedrock, but this turned out to be untrue.

"It's not bedrock beneath the till, it's actually sediments," Gustafson said. "There's groundwater within those sediments that can flow up and down, so it's like an aquifer." Water moving within the sediments can contribute to the ice base, help lubricate the ice flow, or even slow ice flow by pulling water away from the base of the ice.

"We can think about the sediments holding the water as a water-saturated sponge," Gustafson added. Although the researchers weren't able to determine the volume of the groundwater, its depths ranged from 220 to 820 meters (up to about half a mile). Ice above the measured groundwater is similarly thick, and Antarctic ice elsewhere can be up to 4 kilometers (2.5 miles) thick.

Groundwater's Outsized Impact

On the basis of the salinity of the water at those varying depths, the researchers demonstrated an exchange between seawater and fresh meltwater from the ice stream. This interplay confirms that deep groundwater systems could affect ice streaming, an important transport system that carries ice from the continent's interior to the sea. Cumulative changes in ice mass in Antarctica and Greenland are climate change indicators, and warmer temperatures have sped ice flow in recent years, according to the U.S. Environmental Protection Agency.

Geophysicists suspected there might be more and deeper groundwater than they'd observed in earlier research, but Gustafson and her team were the first to prove them right using MT and passive seismic data. It wasn't an easy task.

Antarctica's Challenging Conditions

For Gustafson, being one member of a four-person team camping on the ice sheet for 6 weeks meant labor-intensive days spent not only placing instruments and gathering data but also weathering heavy winds, regularly removing snow buildup from around her tent, and completing camp chores.

"Ice sheets are pretty remote. It's hard and expensive to get there," said Schroeder. Researching groundwater systems on any continent is a challenge, he continued, "but piling between 1 and 4 kilometers of ice on top makes it even harder."

Despite those challenges, he expects groundwater to be incorporated into new models of ice streams for both Antarctica and Greenland as researchers seek to understand what Gustafson's finding means for upcoming changes in ice mass in the face of climate change.

"When you have this big reservoir of water beneath the surface that has the potential to interact with water at the base of the ice sheet, that water can have a lot to say about where the ice above it flows," Schroeder said.

By **Robin Donovan** (@RobinKD), Science Writer

Loss of Ocean Memory Has Implications from Forecasting to Conservation

"Ocean memory," or the persistence of sea surface temperature anomalies, is a key factor in forecasting major climate events. Now, a new study explains how climate change will cause this memory to become shorter, leading to faster changes and reduced warning for events like marine heat waves and extreme rainfall.

The research linked this loss of ocean memory to a thinning of the mixed-layer depth, a layer of water near the surface characterized by uniform density and stability.

"This is really important," said Fei-Fei Jin, an atmospheric sciences professor at the University of Hawaiʻi (UH) at Mānoa's School of Ocean and Earth Science and Technology and a coauthor of the study. "If this layer gets shallower, we lose that predictability because it tends to cool down or warm up much more quickly."

Researchers published their findings in *Science Advances* (bit.ly/ocean-memory). It's the first time scientists have described the decline in ocean memory or linked it to the mixed-layer depth.

Lead author Hui "Daisy" Shi, who was a postdoctoral researcher at the Farallon Institute in Petaluma, Calif., at the time of the study and now works at the Cooperative Institute for Marine and Atmospheric Research at UH, said researchers were surprised by the findings.

"It was totally unexpected," she said.

Elegant Explanation

The researchers were originally working on a different project. Shi was leading an interdisciplinary team from the Farallon Institute investigating marine heat waves along the U.S. West Coast. The group wanted to know whether marine heat waves would become more prolonged, so they looked at data on the persistence of temperature anomalies.

The main factor causing the mixed layer to shrink is warming of water at the surface; this warmer water becomes lighter and less dense, making it harder for the wind to push it down.

"What we found was this decreasing trend in persistence," she said. "We found that very interesting." No previous research had recorded that observation, she noted.

Looking for ways to explain the trend, the team partnered with Jin, who found the connection to the mixed-layer depth.

"The mixed-layer depth will become shallower with global warming, which has already been shown by other research, and when it's shallower, it has less thermal inertia, which translates directly to memory," Shi said. "So it explains [the phenomenon] in a very elegant way that is actually quite simple."

A Thinning Mixed Layer

The mixed layer is caused by wind interacting with the ocean's surface and pushing surface-level water down, causing it to mix with seawater below.

The main factor causing the mixed layer to shrink is warming of water at the surface; this warmer water becomes lighter and less dense, making it harder for the wind to push it down, Jin explained.

Other processes, including the energy exchange between the atmosphere and the ocean, and changes in ocean currents also contribute to changes in ocean memory, researchers said, but the thinning of the mixed layer is most important in most parts of the globe.

The researchers applied several computer models that all showed that a thinning mixed-layer depth would result in a shorter persistence of ocean temperature, Jin said, adding that he expects observational data will make the trend more noticeable as temperatures rise.

"Global models are simulating this very robustly, so I feel this will occur more evidently in the next 30 years," he said.

Implications for Industry

In addition to weather forecasting, the findings have important implications for fisheries management and marine conservation, said William Cheung, a marine ecologist and fisheries scientist at the University of British

J K/Unsplash

Columbia who was not involved with the research.

For example, marine heat waves severely affect coral reefs by causing extensive coral bleaching, and many conservation plans call for mitigation measures to be taken ahead of expected heat wave events.

"This model may not apply equally over the globe, but it applies to most parts of the ocean."

"If this shortens the amount of time we have to prepare or increases the uncertainty associated with these predictions, that can substantially reduce the effectiveness of mitigation measures that help us adapt to climate extremes," Cheung said.

That might mean that conservation programs need to focus on different mitigation approaches or invest in infrastructure to enable a more rapid response, he said.

The paper also raises important questions about how fish stocks will adapt to temperatures that aren't just rising but also becoming more variable, he added.

Jin noted that although the researchers' model applies to most of the world's oceans, they found some important exceptions, including tropical regions. That's because in these areas, El Niño weather patterns can cause ocean temperatures to change not exponentially as they do in other parts of the world, but in an oscillating pattern. To be more accurate, models would need to account for the speed of this oscillation in addition to changes in the mixed-layer depth.

Other regions, such as the North Atlantic, have deep-ocean convection or other processes that have a compensating effect on the trend, Jin added.

"This model may not apply equally over the globe, but it applies to most parts of the ocean," he said.

Jin said researchers hope to do more work to quantify these changes and develop more complex models that account for these factors in equatorial and other regions.

By **Ilima Loomis** (@iloomis), Science Writer

Fossil Fuels Drive an Increase in Atmospheric Helium

The release of carbon dioxide (CO_2) during the extraction and burning of fossil fuels has contributed to major changes in Earth's atmosphere in the centuries since humans realized their value as an energy source. Often accompanying CO_2 are benign gases like helium (He) that can be used to trace such emissions.

Scientists have long speculated that the amount of ^4He—an isotope of helium—in the atmosphere is increasing because it is found in the same reservoirs as natural gas and other hydrocarbons. But measurements have so far been conflicting and imprecise. Now, researchers have developed a new way to measure the noble gas, shedding light on the decades-old conundrum.

"With our measurements, for the first time, we're able to demonstrate that [the theory is] actually true, that helium concentrations in the atmosphere are increasing," said Benjamin Birner, an atmospheric chemist and postdoctoral researcher at Scripps Institution of Oceanography.

The new discovery could lead scientists to better identify sources of CO_2 in the atmosphere, which could guide policies to curb emissions. The increase in ^4He also raises questions about its isotopic companion, ^3He, and a potential undiscovered reservoir of the gas—a critical resource in some research and commercial industries.

Helium Pairs with Fossil Fuels

Some minerals naturally contain uranium and thorium. These radioactive elements decay to stable ones over millions of years, releasing ^4He in the process. Because ^4He is a noble gas, it does not readily bond with other elements and slowly leaks out of its host crystal over time. Rogue helium in Earth's crust percolates toward the surface before escaping to the atmosphere.

In some cases, the rising gas gets trapped beneath an impermeable cap rock. Natural gas, escaping from buried source rocks, also rises through the subsurface and becomes trapped along with helium. "If you have a geological setting that's suitable to contain [natural] gas, it's probably also suitable to trap the helium," Birner said.

When humans come along and extract the gas from these reservoirs, ^4He is also liberated. With the growth of fossil fuel use since the beginning of the industrial era, ^4He should have been flooding the atmosphere. And scientists have been looking for it. Unfortunately, conflicting data have so far muddled any evidence of a long-term rise in atmospheric helium—some studies measured an increase, whereas others showed little to no change.

A Precise ^4He Measurement

Birner and colleagues developed a new way to calculate ^4He to a precision higher than that achieved by any previous studies.

First, they obtained samples. Because of helium's leaky nature, air samples are difficult to store, and scientists have had to mine creative sources of old air. One past study extracted air from inside carburetors and sealed metal pétanque game balls. "[Helium] doesn't diffuse through metals. So you had to find some good metal boxes," said Bernard Marty, a geochemist at the University of Lorraine who was not involved with the study. Birner and colleagues used gas stored in metal tanks sporadically collected by scientists for other experiments since the 1970s.

"If you have a geological setting that's suitable to contain [natural] gas, it's probably also suitable to trap the helium."

Then the group measured the change in the ratio of ^4He and nitrogen (N_2) through time. Nitrogen levels in the atmosphere remain relatively constant over the years; therefore, any change in the ratio between samples indicates a change in the amount of ^4He. The researchers discovered a significant increase in ^4He in air samples dating back to 1974—2 orders of magnitude more than what would be expected from Earth's natural processes, according to the study. The increase is also larger than the small amount released by commercial and research applications.

ISS Expedition 27/NASA

Because ^{4}He can now be precisely measured and is demonstrably increasing, scientists can trace the origins of associated greenhouse gases such as carbon dioxide. ^{4}He concentrations are highest in natural gas compared with other fossil fuels such as coal and petroleum. By measuring the amount of both ^{4}He and carbon in an air sample, scientists hope to determine how much of the total emissions comes from natural gas burning as opposed to automobiles or coal power plants, Birner said.

Surprisingly, scientists also still have a lot to learn about Earth's natural carbon emissions. Having a precise way to trace carbon with helium could help them determine how much is being pumped into the atmosphere by nature, said Marty.

"I think we'll learn a lot more about how the world works from helium," Birner said.

A ^{3}He Mystery

The new data settle the long-standing debate about ^{4}He in the atmosphere. "They are great measurements," said Marty. But, he added, they pose an interesting problem.

Earlier studies, including some by Marty and colleagues, investigated the ratio of ^{3}He to ^{4}He in air samples to get at the ^{4}He concentration in the atmosphere. ^{3}He is a naturally occurring, stable isotope of helium. The most precise ^{3}He/^{4}He measurements available have shown that the ratio is unchanging in the atmosphere over time. That the researchers in this study independently observed an increase in ^{4}He means that ^{3}He must also be increasing.

"People have thought about flying to the Moon to mine ^{3}He there. That's how important that resource is."

^{3}He is rare on Earth; it is released primarily from a mantle reservoir remnant from the formation of our planet. It is also produced from cosmic ray bombardment, solar wind, and interstellar gases and in the manufacture of nuclear weapons. But none of these sources can account for the amount entering the atmosphere. "The signal is about 10 times the geological fluxes, and we don't know how to explain the source of this additional ^{3}He," Birner said.

^{3}He is used in applications such as cryogenics, nuclear fuel, and medical imaging. In recent decades, as demand on the world's supply has increased, it has become a scarce resource. The prospect of an undiscovered source of ^{3}He is therefore intriguing. "People have thought about flying to the Moon to mine ^{3}He there. That's how important that resource is," Birner said. "It will become even more important in the future because nuclear fusion reactors are theorized to run on ^{3}He," he added.

By **Jennifer Schmidt** (@DrJenGEO), Science Writer

Newly Discovered Lake May Offer a Glimpse into Antarctica’s Past

Although it is not tiny, Lake Snow Eagle was easy to miss. The lake is estimated to be 48 kilometers (30 miles) long, 14 kilometers (9 miles) wide, and 198 meters (650 feet) deep but is buried 3.2 kilometers (2 miles) under ice in Princess Elizabeth Land, nearly 500 kilometers (a few hundred miles) from Antarctica’s coast.

A new study has revealed not only how an international team of scientists discovered the lake using aerial ice-penetrating radar but also how the discovery may lead to a fuller understanding of the evolution of the East Antarctic Ice Sheet (bit.ly/subglacial-lake-Antarctica).

Shuai Yan, a graduate research assistant at the University of Texas at Austin, said that although researchers previously had “decent” measurements of the surface of the ice sheet, they lacked similar information about the area below. “We simply didn’t have any data from this region until we went and did the fieldwork,” he said.

Yan and the other researchers said the first hint that the lake and its host canyon even existed emerged when scientists spotted a smooth depression on satellite images of the ice sheet. The team then spent 3 years flying systematic surveys over the site with ice-penetrating radar and sensors that measure minute changes in Earth’s gravity and magnetic field.

Yan was the one who spotted the lake itself during the ICECAP 2 (International Collaborative Exploration of Central East Antarctica through Airborne geophysical Profiling) field campaign, which was conducted in 2018–2019 with logistical assistance from the Australian Antarctic Division and in partnership with other international collaborators.

Yan made the discovery during an overnight data-processing session. “We fly in the daytime, and I wasn’t on that specific flight. I was the one who processed the data overnight to make sure the data was good and everything was working well,” he explained. “Around midnight, I was sitting in front of where the radargram is processed, and on the screen we saw this beautiful, bright reflection.”

That reflection was the lake hidden below the ice.

Shuai Yan (fourth from the right) and the team that conducted an airborne geophysical survey over Lake Snow Eagle pose in front of one of the aircraft involved in the survey. Credit: Shuai Yan/UT Jackson School of Geosciences

The Next Steps

The researchers said sediments trapped beneath Lake Snow Eagle could reveal clues about a time when Antarctica had no ice at all—a sparsely documented period more than 34 million years ago—as well as about glacial cycles since then.

“There is a significant amount of sediment at the bottom of this lake, and we believe these sediments could be an archive of what Antarctica was like before it froze over, how it froze, and the evolution of the ice sheet during the glacial cycles since then,” Yan said.

Martin Siegert, a coauthor, glaciologist, and professor at Imperial College London, agreed. “Our knowledge is based on sediments at the ice sheet margin or offshore,” he explained. “A lake record would be in situ (from beneath the ice sheet itself) and so would be definitive in its information, rather than just clues that need to be unraveled from existing records.”

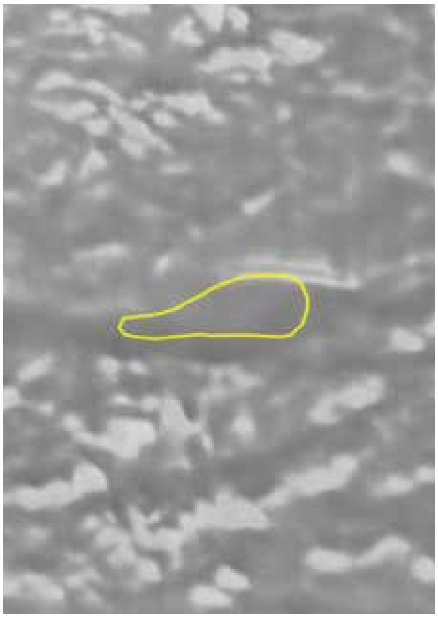
“Around midnight, I was sitting in front of where the radargram is processed, and on the screen we saw this beautiful, bright reflection.”

Tobias Staal, a research associate in Antarctic seismology working for the Australian Centre for Excellence in Antarctic Science who was not involved with the new research, said the lake’s existence has been suggested for a while but there had been large uncertainties.

“The paper presents one of the first detailed insights of any kind into the region,” Staal said. “Previously, we only had satellite-derived data and some rather uncertain extrapolations to map the interior of Princess Elizabeth Land.”

Staal said airborne geophysics provides some significant insight into subglacial geothermal heat flow and erosion/deposition of sediments. However, there is still much more to investigate with denser flight lines, ground-based investigations using seismic surveys, and even, potentially, drilling.

Yan said the team’s future goal is to secure funding to extract sediment samples from the lake bed.



Newly discovered Lake Snow Eagle is outlined in a black-and-white satellite image of the Antarctic Ice Sheet. Credit: RADARSAT/European Space Agency, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

"We believe this lake could be an ideal target for direct coring," Yan said. "It would be really challenging to drill through 2 miles of ice and a few hundred meters of water, but it would be exciting and scientifically important to one day have a sample from that sediment."

Staal advised that such a program would also be very costly and should be discussed in the context of other data gaps.

Adriana Ariza-Pardo, a geoscientist and Antarctic researcher at GMAS consultants in Colombia who also was not involved in the new research, attested to the challenges from her own experiences there but agreed that Antarctica is an important place to study.

"Antarctica is experiencing several changes in its environment, the most notable being those related to the loss of mass of glaciers, the extent of sea ice, the collapse of ice shelves, the increase in air temperature, along with the consequences that these variations generate in the particular Antarctic ecosystems and the rest of the planet," Ariza-Pardo said. "A method to understand these changes can be done through sediment provenance studies, among other geoscientific methods."

By **Andrew J. Wight** (@ligaze), Science Writer

A Community-Led Landslide Prediction System in India

Community scientists, with the assistance of professional researchers, have developed a meteorology-based landslide prediction system for India's Western Ghats mountain range, according to a paper published earlier this year (bit.ly/Satark-India). Called Satark, the model is capable of predicting landslides along India's mountainous southwestern coast a day in advance with an accuracy of 76.5%.

Thirteen out of 15 authors of the paper are community scientists with nonmeteorological backgrounds, including banking, journalism, mechanical engineering, and microbiology. They are part of Center for Citizen Science (CCS), a volunteer-led nongovernmental organization based in Pune, India.

"In 2014, a mudslide occurred in Malin [in the Pune District], and the entire village was buried under debris. Around 150–200 people died. And when we checked past records, we saw that such events are common to Malin and even generally across the Western Ghats," said J. R. Kulkarni, lead author of the paper. Kulkarni is a trustee at CCS and was previously a meteorologist with the Indian Institute of Tropical Meteorology (IITM), Pune, and the World Meteorological Organization.

Scientists found that meteorological conditions like rainfall, as well as geologic factors like slope, soil type, and land cover, were common to such events. "In a nonearthquake and noncyclone scenario, rainfall is the only trigger," Kulkarni pointed out.

Science and Community Collaboration

Prior to collaboration, scientists and CCS worked independently to monitor rainfall patterns in the Western Ghats. Researchers gathered rainfall data from the Tropical Rainfall Measuring Mission (TRMM) and radar data for two points in the Western Ghats: the city of Mumbai and the state of Goa. The model also relied on weather forecasts from the Indian Meteorological Department (IMD). The paper lists 54 rainfall-triggered landslides in the Western Ghats between 2000 and 2016 and notes that the highest frequency of landslides occurs in July and August—peak monsoon months in India.

Meanwhile, volunteers at CCS identified landslide-prone sites in the Western Ghats. They also worked with scientists to identify rainfall thresholds that could trigger landslides. "We [community volunteers] visited the landslide-prone areas, and with the help of meteorologists [like Kulkarni] and geologists, we were able analyze our hypotheses with data and technology and develop a prediction system," said Mayuresh Prabhune, one of the authors of the paper and a journalist by profession. Prabhune is also the secretary at CCS.

Together the two groups tracked rainfall intensity and duration. In India, not all locations have weather monitoring stations to track such patterns, and this is where communities help fill a crucial gap in both monitoring and preparedness.

The team distributed rain gauges to around 50 people across the Western Ghats and also provided training on how to take measurements and read scientific literature. With these tools, communities could measure and assess rainfall data on their own.

"They don't have to wait for data from IMD or anyone else," Prabhune said. They also can take precautionary measures if the data they are tracking show threshold breaches for a continuous period.

"When rainfall begins in the monsoon season, we ask people to keep watch. And if intense rainfall persists for 3 days, they

Monsoon rains blanket the Western Ghats in Manipal, Karnataka, India. Credit: KV 192/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0) know that it is now the ‘alert stage,’” Kulkarni explained. The next stage is “warning,” wherein rainfall breaches thresholds for the next 3 days and the risk of landslides is greater than 90%. Once this stage is reached, residents are encouraged to temporarily move to safer locations.

Incidents like landslides and river floods are not monitored single-handedly by any meteorology department and require interdepartmental and interministerial cooperation and data sharing. “This is where citizen science networks can play a major role.”

The team at CCS provides alerts to a broader audience via a website, social media, and messaging platforms like WhatsApp.

In many instances, “taluka [local administration] officials have contacted CCS for information on rainfall and landslides,” Prabhune said, pointing to the scope of opportunities for collaboration between communities, scientists, and policymakers. The strength of the Satark model, he continued, is that because local people are already involved in the scientific studies and measurements, the task of spreading awareness is reduced.

Climate Change

Climate change is intensifying the need for a landslide prediction system based on meteorology, said Roxy Mathew Koll, a climate scientist with IITM. Both the frequency and the intensity of cloudburst and extreme rainfall events have increased in the Western Ghats, he said, and although the IMD has a system to monitor and forecast weather events, “being a national agency, it may not be always feasi very local level.”

Also, Koll added, incidents like landslides and river floods are not monitored single-handedly by any meteorology department and require interdepartmental and interministerial cooperation and data sharing. “This is where citizen science networks can play a major role,” he said.

Other community-led rainfall measurement efforts (like the Meenachil River–Rain Monitoring project in Kerala) have also demonstrated how communities, and school students in particular, can fill crucial gaps in areas like flood preparedness merely by tracking rainfall and water levels.

Satark is “an interesting decision-making system” based on simple rainfall thresholds, said Rajeevan Madhavan Nair, former secretary of the Ministry of Earth Sciences in India. Overall, he added, it is “an excellent initiative to involve people to do socially relevant research work.”

Noting how measuring rainfall is often part of school syllabi but rarely put to use, Prabhune said that “even school students are very enthusiastic to take rainfall measurements. All you need is an interest in science.”

As the next step, Koll suggested having a set of guidelines to make such monitoring activities uniform across India. “Quality-controlled data from calibrated rain gauges can go back to IMD and can be used for research and forecast purposes,” he said.

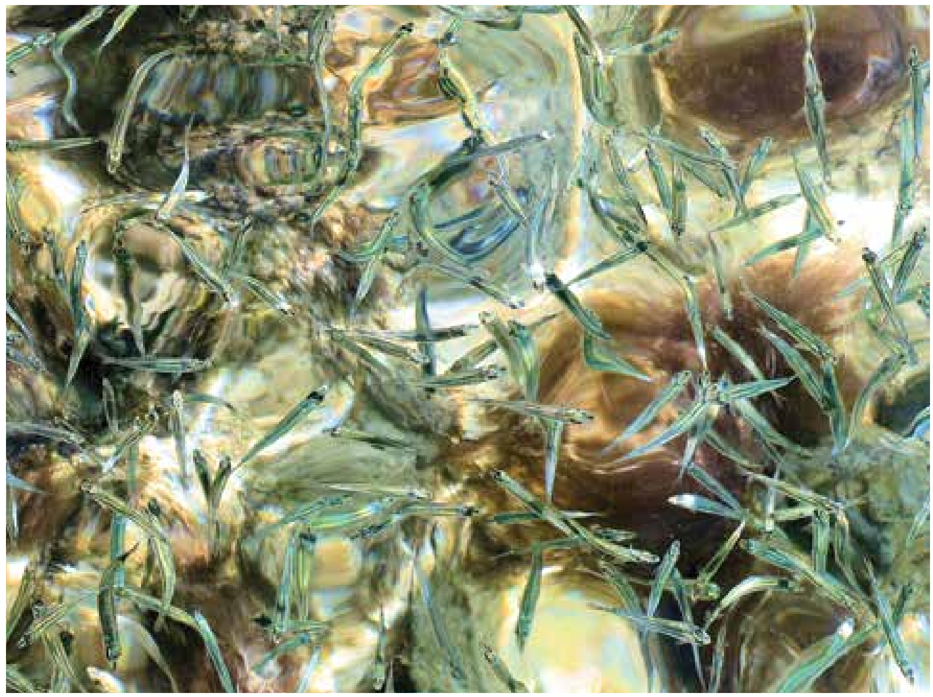
By **Rishika Pardikar** (@rishpardikar), Science Writer

Tiny Creatures May Play a Difficult-to-Detect Role in Ocean Mixing

Beneath the calm surface of the water off the Galician coast of the Iberian Peninsula, anchovies gathered to spawn. While these fish were getting lucky, seafaring scientists got lucky too—for the first time, researchers observed tiny creatures agitating the water enough to contribute to ocean mixing.

It may not be intuitive that little fish swimming in a big ocean can produce mixing on a scale larger than themselves, said John Dabiri, a fluid dynamicist at the California Institute of Technology in Pasadena who wasn't part of the work. The idea wouldn't seem so far-fetched, however, to those who study fluid dynamics.

> **"I guess somebody forgot to tell the animals."**



Anchovies may contribute to ocean mixing in shallow coastal waters. Credit: Paul Harrison/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

The concept of biomixing dates back to the 1960s and to oceanographer Walter Munk, who raised the idea of animal mixing in the ocean as a joke, Dabiri said. More recently, he continued, researchers have tried to declare the idea dead on multiple occasions, publishing papers saying it wasn't possible (bit.ly/generated-mixing). "I guess somebody forgot to tell the animals."

In the lab, Dabiri's team has documented turbulent mixing from swimming brine shrimp (bit.ly/turbulent-mixing).

Although those critters don't dwell in the ocean, their motions mimic the nightly vertical migrations of ocean-abundant krill, showing that mixing due to vertical migrations is physically possible. Other researchers have spotted creature-caused turbulence in the ocean but haven't been able to tie it to mixing of layers of water with different properties, such as temperature or salinity. Still others have tried to measure mixing by shoals of fish and have come up empty. The lack of evidence prompted some researchers to maintain that biomixing doesn't occur, Dabiri said.

A Fishy Surprise

Then, in the summer of 2018, scientists who knew a thing or two about ocean turbulence happened to be in the right place at the right time. "It was a fortuitous observation," said Bieito Fernández Castro, an oceanographer at the University of Southampton in the United Kingdom and lead author of a study published in *Nature Geoscience* (bit.ly/upper-ocean-mixing). Fernández Castro and his colleagues, on a project led by University of Vigo researchers from Spain, were planning to study a different topic—how turbulence affects the growth of algae that produce toxins. Blooms of this algae typically don't occur when there's turbulence, so the team had picked a spot where they thought there would be little ocean mixing, Fernández Castro said.

For 15 days, the researchers waited in the same spot for the bloom to appear. To detect turbulence, they used a tool that senses small-scale temperature and velocity fluctuations. They let the instrument fall in the water and brought it back up repeatedly, like a yo-yo. During the day, the water's turbulence was weak. But each night, they measured strong turbulence at 10 meters and deeper. "The values of turbulence we were getting were just huge," Fernández Castro said. "We were thinking this should feel like a big storm."

At first, that puzzled the scientists. "It was very funny to be on this cruise," Fernández Castro noted. It took a few days to rule out wind and tides as the cause of the turbulence.

The ship happened to have an instrument that provided a vital clue. The vessel, which is also used for fisheries research, was equipped with a device that uses sound waves to spot the presence of fish. A nightly uptick in the acoustic signals corresponded to the ocean commotion.

The team didn't have quite everything needed to study fish, so they improvised. Each night, they cast their plankton nets into the water and hauled in a load of anchovy eggs, suggesting that the mingling and mixing fish were spawning.

"When we realized what it was, we got very excited because we know about all this controversy [about biomixing]," Fernández Castro said. This controversy has continued, in part, because it's been tricky to find turbulent mixing in the wild.

"The values of turbulence we were getting were just huge. We were thinking this should feel like a big storm."

Mixing to Fuel Life

It's not clear how widespread biomixing is. Fernández Castro and his colleagues caught this ocean agitation in a relatively shallow embayment where properties such as temperature have a sharp gradient. This may be one of the requirements for small creatures to stir up the ocean, the authors wrote. In the deep ocean, where such gradients aren't as strong, small fish may not be able to impart enough energy to mix layers of water together.

The team wasn't sure whether such mixing occurs in other parts of this bay, let alone in other ecosystems. But where it does occur, such mixing could fuel life. Vertical mixing brings oxygen that's plentiful in the upper waters down to the depths, where it helps sustain life on the seafloor. And mixing can carry nutrients, which come from the sunken remains of algal die-offs, back to the surface. "Anything that promotes vertical exchange in stratified waters is generally good for the ecosystem because it provides what is lacking," Fernández Castro said.

As a connected network, the ocean's transport of carbon, oxygen, and nutrients and its density structure could be affected by biomixing, Dabiri said. And if this mixing is found to occur on a wider scale, it will present a computational challenge for researchers who model the ocean's climate and circulation. Although we can't yet rule out that biomixing isn't happening on a large scale, Dabiri said, it's hard to overstate the impact it could have.

By **Carolyn Wilke** (@CarolynMWilke), Science Writer

Crowdsourced Weather Projects Boost Climate Science Research

In 1895, the Seathwaite observing site in southwestern England had multiple rain gauges. Credit: Met Office

Thousands of volunteers, immobilized by the COVID-19 lockdown, recently revived a trove of historic rainfall records from the United Kingdom and Ireland. The handwritten archives note rainfall observations from landowners, socialites, and an array of eager citizens dating back to the late 17th century. Computer software cannot yet accurately decode handwriting, so human eyes were critical.

Researchers with the Rainfall Rescue project tasked volunteers with manually transcribing 3.34 million observations to make the data available for scientists to study Earth's past climate.

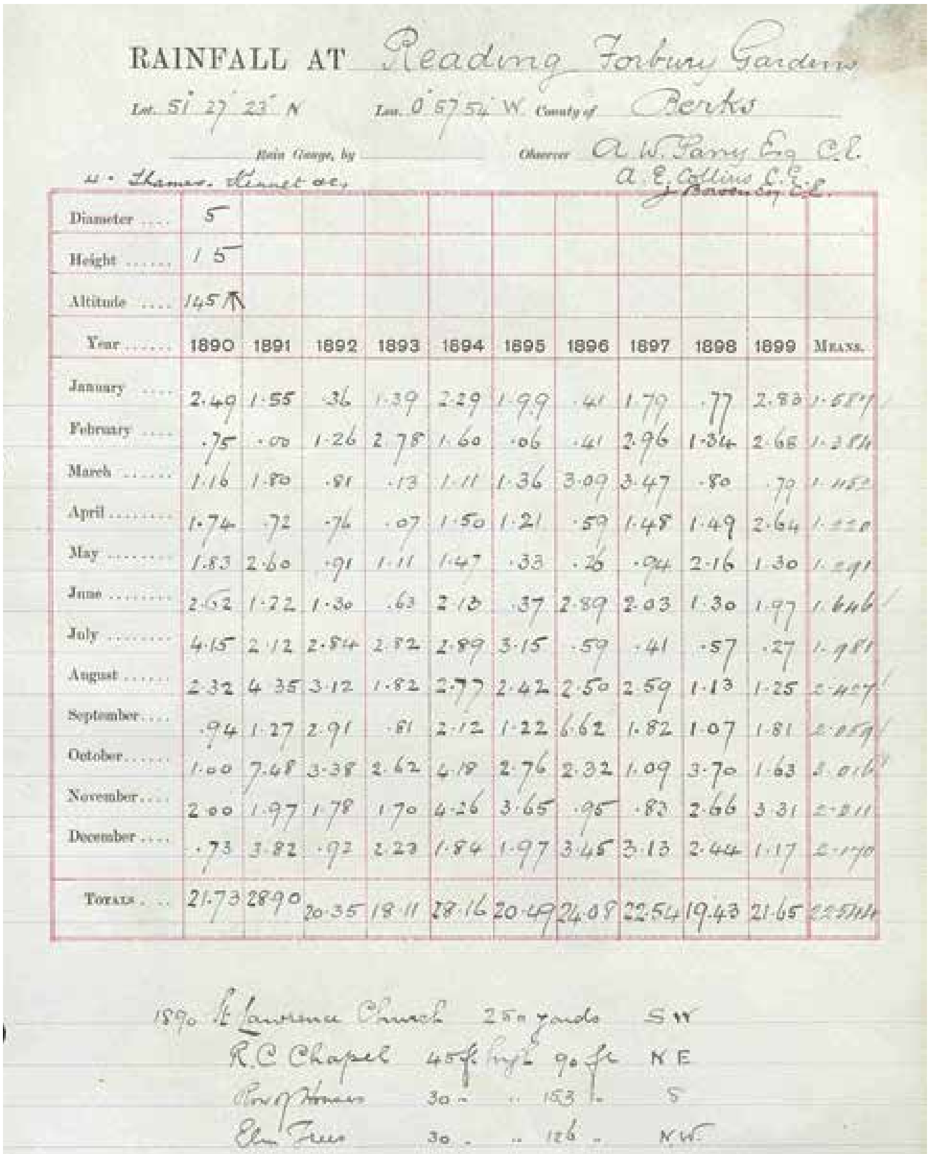
"We were expecting this to take months," said Ed Hawkins, a climate scientist at the University of Reading and lead author of the newly published study describing the effort (bit.ly/Rainfall-Rescue). "We got through it in 16 days."

The documents contained enough data to extend detailed weather records back to 1836. In doing so, the researchers crowned 1855 the new driest year on record for the region. "We have rewritten the record books, if you like," said Hawkins, "by going backwards, not forwards."

Rescued Records Inform Climate Science

High-resolution weather reconstructions combine meteorological observations with algorithms describing atmospheric physics to iteratively produce a near-hourly estimate of global climate over past decades or even centuries. They are a time machine for climate scientists looking to evaluate long-term trends or interrogate past events. Historic data such as those recovered from the United Kingdom and Ireland can help validate a reconstruction, said Laura Slivinski, a physical scientist with NOAA and the colead on the Twentieth Century Reanalysis Project (version 3), which generated a global atmospheric data set of weather spanning 1836–2015.

Historic data document some particularly extreme events, and that can help scientists understand why and how such events happen, said Drew Lorrey, a climate and environmental scientist at New Zealand's National Institute of Water and Atmospheric Research. "That's really powerful, because we can then look in our modern models for similar patterns that are rising months into the future and use that as an early-warning system."


RAINFALL AT Reading Forbury Gardens

Lat. 51° 27′ 23″ N Lon. 0° 57′ 54″ W. County of Berks

Rain Gauge, by ______ Observer A. W. Parry Esq C.E.

W. Thames. Kennet &c, A. E. Collins C.E.

Diameter	5										
Height	1 5										
Altitude	145 ft										
Year	1890	1891	1892	1893	1894	1895	1896	1897	1898	1899	Means.
January	2.49	1.55	.36	1.39	2.29	1.99	.41	1.79	.77	2.83	1.589
February	.75	.00	1.26	2.78	1.60	.06	.41	2.96	1.34	2.66	1.384
March	1.16	1.80	.81	.13	1.11	1.36	3.09	3.47	.80	.79	1.452
April	1.74	.72	.76	.07	1.50	1.21	.59	1.48	1.49	2.64	1.220
May	1.83	2.60	.91	1.11	1.47	.33	.26	.94	2.16	1.30	1.291
June	2.52	1.72	1.30	.63	2.13	.37	2.89	2.03	1.30	1.97	1.646
July	4.15	2.12	2.84	2.32	2.89	3.15	.59	.41	.57	.27	1.981
August	2.32	4.35	3.12	1.82	2.77	2.42	2.50	2.59	1.13	1.25	2.427
September	.94	1.27	2.91	.81	2.12	1.22	6.62	1.82	1.07	1.81	2.059
October	1.00	7.48	3.38	2.62	4.18	2.76	2.32	1.09	3.70	1.63	3.016
November	2.00	1.97	1.78	1.70	4.26	3.65	.95	.83	2.66	3.31	2.311
December	.73	3.82	.92	2.23	1.84	1.97	3.45	3.13	2.44	1.17	2.170
Totals	21.73	28.90	20.35	18.11	28.16	20.49	24.08	22.54	19.43	21.65	[illegible]

1890 St Lawrence Church 250 yards SW
R.C. Chapel 45 ft high 90 ft NE
Row of Houses 30 .. 153 .. S
Elm Trees 30 .. 126 .. NW

Volunteers pored over millions of rainfall records from across Ireland and the United Kingdom as part of the Rainfall Rescue project. This rainfall sheet tracks precipitation at a weather station in Forbury Gardens in Reading, U.K. Credit: Met Office, CC BY 4.0 (bit.ly/ccby4-0)

Records from recent decades show that extreme weather events are becoming more common. "People need to make decisions now about building resilience to the weather in general and how that weather is changing," Hawkins said. "We need to know what a one-in-100-year or a one-in-200-year flood looks like."

Holes Need Filling

Climate reconstructions rely on an enormous database of observations—the bulk of which come from the decades since the proliferation of satellites. Before that time, data are spotty. "The further back in time you go, the fewer observations you have, the more work those observations have to do to bring the whole global estimate towards reality," said Slivinski, who was not involved with the recent study but works with Hawkins and Lorrey on other projects.

Gaps in climate databases are particularly glaring in the Southern Hemisphere, where there is less land from which to make observations, Lorrey explained. These data rescue efforts are key to filling holes, he said.

Lorrey, who was not involved with Rainfall Rescue, leads the Southern Weather Discovery project, which is recovering early 20th-century weather records from stations in New Zealand and Antarctica and ship logs from vessels sailing the Southern Ocean. He and colleagues outlined their approach to crowdsourced record digitization in a paper published in *Patterns* (bit.ly/Southern-Weather-Discovery). Volunteers have so far digitized nearly 250,000 observations from the region.

Although data quality is a concern for the Rainfall Rescue and Southern Weather Discovery records, there's strength in numbers, said Kevin Trenberth, a climate scientist at the National Center for Atmospheric Research and lead author of the 2001 and 2007 Intergovernmental Panel on Climate Change reports. "An observation not made is lost forever," he said. "And here, a lot of observations have been made."

A Shared Experience

Crowdsourced weather data have benefits beyond science. Rainfall Rescue volunteers took to the project's forums to talk about interesting notes they came across in the records, such as one entry from World War II that mentioned a bullet hole in the rain gauge. Sharing their experiences helped volunteers feel like part of a community, Hawkins said. "There are so many good comments on the chat forums about people feeling useful."

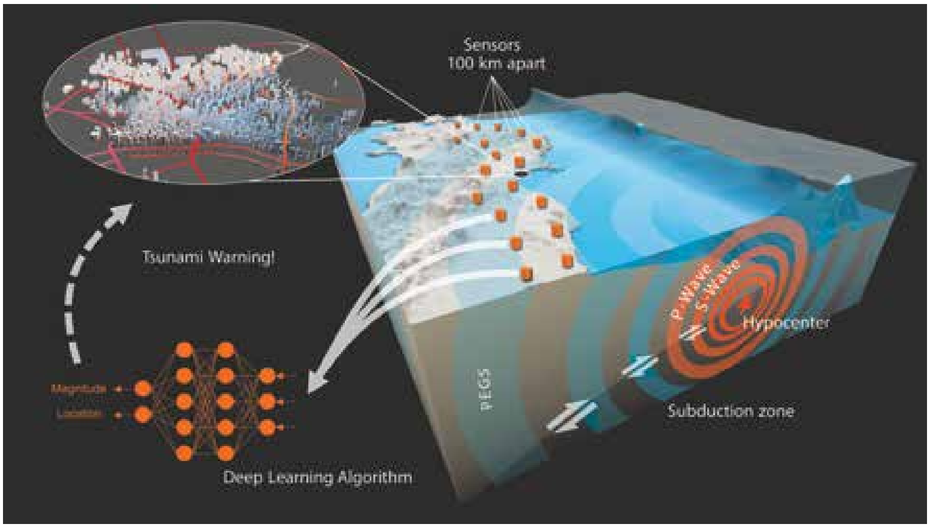
Modern-day rainfall observers continue to provide precious data. Ongoing initiatives such as the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) have been collecting rainfall data from volunteers in the United States for more than 20 years. The project gives people an outlet for their weather curiosity, said Melissa Griffin, the South Carolina CoCoRaHS coordinator.

And CoCoRaHS volunteers are providing more than just numbers; reports filed during Hurricane Matthew in 2016 included comments about which streets were flooded and where animals were on the move to escape rising streams. That information is valuable for distributing resources in an emergency or estimating future water resources, Griffin said.

"You know you are providing data to your community and your community is using [those] data," she said.

By **Jennifer Schmidt** (@DrJenGEO), Science Writer

Monitoring Earthquakes at the Speed of Light



*Scientists recently developed a deep learning algorithm to estimate large earthquakes' magnitudes on the basis of prompt elastogravity signals (PEGS) traveling at the speed of light, much faster than the seismic (*P *and* S*) waves traditionally used in early-warning systems. Credit: Lina Jakaite*

Earthquakes and the tsunamis they generate have caused almost a million casualties in the past 30 years. Many alert systems have been developed to limit the human and material costs of these natural disasters. However, these systems have difficulties in estimating quickly and accurately the magnitude of very large earthquakes.

Now, a study published in *Nature* has described a machine learning model that recognizes patterns in seismic data to better estimate the magnitude and location of a large earthquake (bit.ly/ML-earthquake).

Using 350,000 modeling scenarios of earthquakes initiating at 1,400 potential earthquake locations in Japan, Andrea Licciardi, a geophysicist at the Université Côte d'Azur in France, and his colleagues succeeded in instantaneously estimating the magnitude of large earthquakes on the basis of prompt elastogravity signals (PEGS).

PEGS are gravitational perturbations generated by the motion of large masses of rocks during an earthquake. They propagate at the speed of light, carrying earthquake information much faster than seismic waves traditionally used in early-warning systems.

Scientists have known that although in principle PEGS could help speed up earthquake warnings, their very weak amplitude has prevented their use in alert systems. The researchers in the new study overcame this limitation thanks to an artificial intelligence algorithm based on Global Navigation Satellite System data. Using the algorithm, they showed that the magnitude of large earthquakes could be accurately estimated on the basis of PEGS seconds after the earthquake starts and tracked as the earthquake grows.

"What is innovative in this paper is the use of machine learning techniques, which makes it possible to improve the detection of these very small signals," said Jean-Paul Montagner.

Licciardi agreed. "The main advantage of our model relies on the underlying data, the elastogravity signals," he explained. "Once an earthquake occurs, these signals travel faster than seismic waves and are strongly sensitive to the earthquake magnitude.... Because of that, our model can estimate the magnitude of the earthquake faster and more accurately than conventional early-warning systems based on *P* waves, at least for large earthquakes (magnitude above 8.3/8.4)."

Improving Tsunami Early Warning

Licciardi pointed out that the model's response time of about a minute can dramatically improve tsunami early-warning forecasts. In a real-time scenario, he said, the magnitude retrieved by the model can be used to quickly estimate the size of the induced tsunami wave and therefore mitigate its impact.

"Classical early-warning systems based on *P* waves can't distinguish between a magnitude 8 and a magnitude 9 earthquake, while our model does not suffer from this limitation," said Licciardi. "It provides the most accurate estimation of magnitude as a function of time."

The new model's strength in forecasting large earthquakes "is because the elastogravity signal is strongly sensitive to the magnitude of such large earthquakes," Licciardi explained. "In fact, the applicability of our model is limited to such large earthquakes (magnitude above 8.3/8.4) because the signal's amplitude for relatively smaller earthquakes is too small and buried in the background noise. This is why other tools and data are still needed in the context of early warning."

"This is important for earthquake early-warning systems, because for the largest earthquakes there is an extended time (up to minutes) in which they gather magnitude and strength," explained Andreas Plesch, a senior Earth scientist at Harvard University who was not involved in the new work. "The authors correctly point out that during this extended time, the method, especially if combined with other methods, has the operational potential to track the growth of such an earthquake earlier and more accurately."

"What is innovative in this paper is the use of machine learning techniques, which makes it possible to improve the detection of these very small signals."

Plesch further noted that the new model could enable tsunami alerts to be issued not only earlier (by tens of seconds or perhaps even minutes) but also more confidently and with better wave height estimates derived from improved magnitude estimates.

By **Mohammed El-Said** (@MOHAMMED2SAID), Science Writer

Planting Wetlands Could Help Stave Off Climate Catastrophe

Repopulating forests, planting neighborhood trees, and stopping large-scale logging are popular strategies to offset or reduce carbon emissions. But forests pale in comparison to wetlands' carbon sequestration potential. Peatlands, salt marshes, and other coastal and inland wetlands cover just 1% of Earth's surface, yet they store 20% of our planet's ecosystem carbon, according to new research.

"[Carbon] is billowing out of these degraded wetlands."

Restoring wetlands is a powerful additional tool to combat climate change, said Brian Silliman, an ecologist at Duke University and a coauthor of the study, published in *Science* (bit.ly/restoring-wetlands).

Wetland Plants Hoard Carbon

Plants suck carbon from the atmosphere and use it to grow roots, leaves, and flowers. That carbon is released only when the plants decay and landscapes erode away.

The intricate root systems of partially submerged mangrove stands, salt marshes, and seagrass meadows filter material washing downstream from inland landscapes. The tangled mash of sediments and plant matter becomes the muddy embankment on which more trees and plants grow. Around 50% of the carbon buried in these environments comes from this filtered organic matter, according to the study.

Peatlands are particularly important carbon sinks. Peat moss—a primary ingredient in many boggy wetlands—grows as mats of spongy plant matter. Older peat is buried beneath newer sprouts, and in the submerged, low-oxygen environment, sluggish decay locks in thick mats of carbon for millennia.

Wetlands may be a powerhouse of sequestration and storage, but their limited area means they store a fraction of the total carbon sequestered in oceans and forests—the world's biggest sinks, owing to their sheer size. Nevertheless, a wetland's greater carbon density means that removing a patch of it has a bigger impact on atmospheric carbon than removing a patch of forest.

Around 1% of wetlands are lost each year to such threats as construction, farming, and sea level rise, according to the study. With the loss of these environments comes the release of their stored carbon—accounting for roughly 5% of annual total global carbon emissions. "It's billowing out of these degraded wetlands," Silliman said.

Moving Beyond Just Planting Trees

Although regulations to minimize wetland loss exist, "we haven't been as aggressive as we could be in restoring them. And part of that is because we've underappreciated their importance in the climate crisis," said Peter Kareiva, a conservation biologist and president and CEO of Aquarium of the Pacific, who was not involved in the study. Governments and environmental organizations have initiatives to reforest vast stretches of land, he said, but they haven't had those initiatives at such scale for wetlands. But the recognition that wetlands are vastly more carbon rich than oceans or forests could change that.

"[The study] is a call to action to scale it up," Kareiva said.

Restoring, protecting, and rebuilding wetlands can be both a global and a grassroots strategy. "That's something that people can get involved with locally," Silliman said. "Policymakers who have bigger levers need to think about stopping the degradation of wetlands in a big way," he added.

"Everybody's wondering how to offset their carbon," he said. "Here you go: You plant a wetland. You get a huge bang for your buck."

A Shift in Wetland Restoration

The new study also suggests a change in the approach to wetland restoration efforts. Traditional conservation practices focus on limiting negative interactions among plants and their environment, Silliman said. People plant over small areas and maximize spacing between individual plants to avoid competition. But that's the wrong approach, he said. Isolated plants have little protection from storm surges, and many are lost during planting efforts. Restoring a wetland in this way is also expensive.

iStock.com/Ali Suliman

Emerging research has suggested that mutually beneficial interactions among plants and their environments are crucial to their survival—and to maximizing their prospects as a carbon sink. Planting wetland grasses in clumps gives them a better chance to survive because they are more protected, Kareiva said. Restoration costs go down when success rates go up.

"If you've firmly established a bunch of patches, they sometimes just spread on their own," he explained. "You don't have to plant seedlings everywhere."

By **Jennifer Schmidt** (@DrJenGEO), Science Writer

Climate Change Leads to Decline in Lichen Biocrusts

Biological soil crusts, or biocrusts, are communities of living organisms at the soil surface and are known as the "living skin" of dryland ecosystems. They cement soil grains together, thereby protecting dryland soils from erosion. Biocrusts also add critical nutrients to the soil by converting nitrogen in the atmosphere to ammonia, which serves as a kind of fertilizer for plants and microbes.

Unfortunately, trampling by livestock and such human activity as driving vehicles off-road make biocrust survival difficult. New research published in the *Proceedings of the National Academy of Sciences of the United States of America* has suggested that there's another phenomenon that biocrusts are sensitive to: climate change (bit.ly/biocrusts-climate).

According to Rebecca Finger-Higgens, a research ecologist with the U.S. Geological Survey (USGS) at the Southwest Biological Science Center, the study has a long history. It originally sought to better understand how biocrust communities change over time as well as to address the dearth of studies that assessed the long-term impacts and ecology of biocrusts. "It was a really unique, long-term study started by Jayne Belnap [a USGS soil researcher] back in the nineties," explained Finger-Higgens.

It wasn't until years after the project started that climate change's impacts on biocrusts in the American Southwest became a focus of the project.

Ferran Garcia-Pichel, a biocrust microbiologist at Arizona State University who was not involved in the study, described the length of monitoring as "unparalleled" for biocrust research in the southwestern United States. "It is a great asset.... Somebody was at it every day making sure the data were collected for decades. It's just so rare and so precious," he said.

Losing Lichens

The research was conducted on the Colorado Plateau within the Needles District of Canyonlands National Park in Utah. The protected site was one of the few remaining areas where biocrusts had not been trampled by cattle. Focusing on this pristine location gave Finger-Higgens the rare opportunity to observe how biocrusts behave without any confounding effects of direct disturbance.

The researchers measured the number of lichen and moss species present in biocrusts and the extent of lichen and moss cover. On the basis of the long-term observational data set, they found that both the number of lichen species and the area of land covered by lichens decreased over time. In 1967, lichens covered close to 20% of the land area. By 2019, nitrogen-fixing lichens covered only around 5%. The lichens were partly replaced by mosses, but overall, their loss resulted in a decrease in total biocrust cover.

Increasing summertime temperatures best explained the decline in lichen cover; lichen cover was lowest in years with the hottest maximum temperatures in June.

This new research is one of the first long-term studies to provide field evidence to support the hypothesis that a warming climate is harming lichen biocrusts. However, the authors cautioned that correlation does not equal causation, and the study cannot explicitly link the decline in lichen cover to warming temperatures.

"It is a great asset.... Somebody was at it every day making sure the data were collected for decades. It's just so rare and so precious."

Fewer Lichens, Fewer Soil Nutrients?

Further warming might push lichens to a tipping point after which they will be permanently lost from dryland biocrusts, said Finger-Higgens. Because biocrust lichens have an important role in adding nutrients to the soil, their absence could have cascading impacts on dryland ecosystems.

However, some cyanobacteria and associated heterotrophic bacteria also add nitrogen to dryland soils, and their coverage was not assessed in the study. "Maybe cyanobacteria [cover] went up, we don't know.... But now we have a hypothesis to test," said Garcia-Pichel. "The data only tell you one thing. The lichens uncontroversially went down...and this goes along with an increased summer temperature."

The scientists are continuing their work. They have already begun to test their hypothesis in Canyonlands National Park by measuring the amount of nitrogen that the lichens are adding to soils there.

But even if Southwest biocrusts can stabilize without lichens, Finger-Higgens will be sad to see them go. "Personally, I just like the lichens. I think they are pretty. There is an aesthetic value to them."

Nutrient-providing biocrusts abundant in lichens grow on the soil surface of the Colorado Plateau and protect it from erosion, but the extent of biocrust cover has been decreasing over the past 2 decades. Credit: Rebecca Finger-Higgens

By **Derek Smith** (@djsmitty156), Science Writer

Peat Uncovers a Uniquely Resilient Irish Community

Abandoned settlements, field systems, and cultivation ridges reveal former communities on the Antrim Plateau in Northern Ireland. Credit: Gill Plunkett

Today, Northern Ireland's uplands may seem wild and barren, but in fact, they were occupied and farmed for centuries, enduring crises including the Great Famine, the Little Ice Age, and the Black Death. To researchers, there has been an air of uncertainty around the long-term effects of these stressors on the region's remote, "marginal" communities compared with those in towns and cities like Dublin.

"Reconstructing the impact of past climate change on human societies has long been something of a holy grail for paleoenvironmental and archaeological research."

Slieveanorra is an isolated nature reserve in Northern Ireland's Antrim Plateau. From as early as the 12th century, however, the area was home to several family units engaged in farming and shepherding, although researchers are unsure whether residents were permanent or seasonal. Sparse human occupation of Slieveanorra continued until the early 20th century, when the area's lack of infrastructure and professional opportunities contributed to the last residents permanently abandoning the site.

Gill Plunkett and Graeme Swindles, archaeologists affiliated with Queen's University Belfast in Northern Ireland, dug at Slieveanorra to see how the environment had changed since 1000 CE. After a core of peat was taken from the local bog, they analyzed it for patterns in the prevalence of microbes, pollen, and plant fossils, all proxies for land use. Volcanic ash layers (left by eruptions in Iceland) and organic remains were used to date the layers and mark historically significant periods like the Black Death, Little Ice Age, and Great Famine.

In their *PLOS ONE* study, the researchers present a high-resolution record of Slieveanorra's occupation across a thousand years (bit.ly/Slieveanorra). Proxies show indigenous woodland replaced by grassland cultivation of cereals throughout Slieveanorra's occupied history, until its contemporary uses for recreation and commercial forestry.

Surprisingly, the patterns showed no drastic changes during historical catastrophes. "Had the population been severely impacted by climate or other calamities to the point that its survival in the area was compromised," Plunkett explained, "we would expect to see a cessation of farming indicators, such as cereals, and a recovery of tree pollen as woodland spread out into abandoned areas."

Slieveanorra's Secret to Survival Success

Plunkett and Swindles speculated that the people of Slieveanorra must have been able to either avoid environmental and societal calamities or quickly adapt to them. This observation was unexpected because the Slieveanorra population was quite remote and relatively economically unproductive. The researchers suggested that the cause for such societal robustness comes down to factors like agricultural methods (including the harvesting of both food and fiber crops) and trade.

"We think the population was practicing subsistence farming," Plunkett explained, "including mixed crop cultivation and some animal husbandry. A mixed economy, coupled with the likely availability of supplementary wild resources in the surrounding woodland and rivers, may have helped tide them over during lean years (for example, if a crop failed because of a bad summer). The low population density in the wider area would have minimized the risk of transmission of infectious diseases."

Benjamin Gearey, a lecturer in environmental archaeology at University College Cork, Ireland, said the new study contributes to a more robust understanding of how different communities have adapted to climate change in the past. "Reconstructing the impact of past climate change on human societies has long been something of a holy grail for paleoenvironmental and archaeological research," he said. "This study is an important step forward, providing much food for thought, especially as we confront the contemporary impact of climatic change and ecological crisis."

By **Clarissa Wright** (@ClarissaWrights), Science Writer

Microscopic Hitchhikers Found on Deep-Sea Plastic

Certain types of microbes that live thousands of meters deep in the ocean have a special affinity for plastic surfaces. Scientists want to know which bacteria choose to grow on plastic and whether they could skitch on fragments to travel around the ocean.

A new study revealed the motley crew of bacteria growing on plastic nearly 2,000 meters down in the Atlantic Ocean.

Among them are *Halomonas titanicae,* a rust-loving bacterium first discovered on the *Titanic,* and *Aliivibrio,* a pathogen dangerous to farmed fish. Compared with microbes on natural stone, these bacteria "actually showed an affinity for growing on the plastic as opposed to any hard substrate," said Max Kelly, a Ph.D. student at Newcastle University who led the research.

Fewer than 1% of ocean plastics remain on the surface, and many scientists believe that the deep ocean is the final resting place for humanity's refuse. Deep-sea microbes might be in a unique position to take advantage of the trash: Scientists wonder whether bacteria could hitchhike on plastic carried by ocean currents to travel to new ecosystems.

"Perhaps this influx of plastic is providing stepping-stones across these large ocean distances," said Kelly.

Ocean Floaties

"An experiment like this requires a lot of effort from the researchers," said Julio Cezar Fornazier Moreira, a scientist at the University of São Paulo who was not involved in the work. "Research studies in deep-ocean layers are costly and require a very elaborate logistical strategy to be viable, especially when structures are deployed for long periods. So it is very satisfying to read works like this."

Halomonas titanicae, a rust-loving bacterium first discovered on the _Titanic,_ and _Aliivibrio,_ a pathogen dangerous to farmed fish, were found growing on deep-sea plastic.

The 10 plastic pieces used in the study traveled from Newcastle to the seafloor on a steel-framed Deep Ocean Benthic Observer lander. Oceanographers aboard M/V *Scotia* placed the lander at the Atlantic's Rockall Trough northwest of Scotland in 2015. The lander sat 1,796 meters below the surface for 420 days.

The lander held five plastic cubes of polystyrene, a plastic common in children's toys, and five samples of polyurethane, a typical plastic in household kitchen scrubbers. Over time, bacteria attached and grew on the plastic and stone pieces, each a little smaller than a Rubik's Cube.

When Kelly sequenced the bacteria's RNA, "we found this sort of small and yet really weird community that is able to stick to plastic."

"Plastic is quite hydrophobic. It's hard for natural bacteria to stick." More research is needed to understand how some bacteria cling so readily, said Kelly.

Less than 1% of the bacteria identified preferred only the plastic versus growing on both the plastic and the stone. Among them were Marine Methylotrophic Group 3, microorganisms related to bacteria on methane seeps near New Zealand, and *Spirosoma,* a genus that's known to survive in Arctic permafrost. The hydrocarbon-degrading bacteria from the genus *Oleiphilus* grew on both types of plastic.

"The next step is then looking at potentially what species...can be used for more plastic degradation studies. Ultimately, can we have your plastic degrading in compost bins at home?" Kelly asked. He published the work in the journal *Environmental Pollution* (bit.ly/bacteria-plastics).

"We found this sort of small and yet really weird community that is able to stick to plastic."

"This [study] is interesting because this could represent a habitat where a good amount of plastic debris could come to a final resting place," said assistant professor Tracy John Mincer at Florida Atlantic University who was not involved in the research. "I look forward to seeing a full metagenomic study that can provide a 'parts list' of the genes that are present in these microbes colonizing plastics at depth."

The Deep Ocean Benthic Observer was kept stable on the seafloor by large yellow buoys. The multicolored boxes attached to the lander are the plastic samples. Credit: Newcastle University, Public Domain

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

Glacial Knowledge Gaps Impede Resilience to Sea Level Rise

Earth's ice sheets and glaciers are responding rapidly to climate change. In the years and decades ahead, sea level rise, driven in part by melting ice, will affect millions of people in U.S. coastal communities and hundreds of millions more around the world. The cost of adaptation to sea level change along U.S. coastlines alone is expected to exceed $1 trillion by 2100 [*Neumann et al.*, 2015].

Our ability to accurately and actionably project ice loss and its contributions to sea level rise requires glaciological knowledge and research coordination, as well as effective knowledge dissemination to decision-makers, that are still unrealized. Current ad hoc efforts to meet these needs are inadequate, delaying the benefits of scientific research for many communities already grappling with increased coastal flooding and other impacts [*Wing et al.*, 2022]. Through more coordinated planning and funding efforts, we can better serve these communities.

In addition to improving sea level projections relevant for coastal mitigation and adaptation responses, expanding our knowledge of glacial processes (including those influencing mountain glaciers) improves our understanding of how climate change affects agriculture, hydropower, drinking water, fisheries, and ecosystems. For example, research has revealed that mountain glacier retreat along the North American West Coast opens new habitat for Pacific salmon, affecting billion-dollar-per-year fisheries [*Pitman et al.*, 2021]. It has also shown that the worldwide annual net loss of 240 billion metric tons of ice from mountain glaciers is comparable to 30% of annual water withdrawals for industry and 63% of water withdrawals for domestic uses [*Huss et al.*, 2017].

A great deal of glaciological knowledge has come about from a boom in glaciological research during the 2000s, which drew many new researchers to the field. Many of them are asking urgent questions prompted by the discovery that Earth's ice sheets respond to environmental forcing on much shorter timescales than previously thought.

Decades of glaciological research have resulted in huge improvements to prediction of sea level change. However, major gaps in glaciological understanding, observational data, and technical capacity persist and impede efforts to produce actionable predictions of ice loss directly linked to societal consequences (Figure 1). For example, we have only sparse observations from ice sheet boundaries, including the edges of marine-terminating glaciers and ice sheets where ocean currents influence ice loss. We lack a basic understanding of what happens between glacier ice and the underlying land, where topography, sediments, and subglacial water influence ice motion. We also lack sufficient long-term monitoring of climate conditions that are forcing ice sheet change, including ocean heat content, which was recently recognized as critically important to both the Greenland and Antarctic ice sheets.

A weather station collects data above LeConte Glacier, near Petersburg, Alaska. Credit: Twila Moon, NSIDC/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Despite the serious implications of coastal inundation and other ice loss impacts, research on Earth's glaciers and ice sheets remains a low funding priority in the U.S. scientific enterprise (see Figure 2 at bit.ly/Eos-glacial-knowledge) [*Aschwanden et al.*, 2021]. This low standing is not for a lack of identifying critical scientific problems or their societal relevance. Indeed, the knowledge gaps noted above have been identified in numerous published studies and are well known to federal and international funding agencies, scientific organizations, and the scientific community [e.g., *Catania et al.*, 2020; *Hock et al.*, 2017; *Noble et al.*, 2020; *Straneo et al.*, 2019]. Instead, we perceive other shortcomings that stymie innovation in glaciology and its contributions to accurate projections of ice loss and, by extension, U.S. resilience to sea level.

Culture, Curriculum, Organization, and Funding

Glaciology suffers cultural shortcomings common across the geosciences, specifically a historic and ongoing lack of gender, ethnic, and racial diversity that makes the discipline inequitable [*Bernard and Cooperdock*, 2018; *Dutt*, 2020]. Part of this problem arises because popular conceptions of glaciology are rooted in hero-glorifying expeditions led by a small number of individuals, while the contributions of many others in the field go underrecognized. This conceptualization narrows the range of visible role models, reduces chances for diversity benefits within our field, creates a tone of elitism and exclusivity, and is unethical.

This culture makes it difficult for minoritized researchers (demographic groups relegated to a subordinate status, regardless of their actual numbers) to enter the field, contribute productively, and be valued and evaluated fairly, resulting in the near-complete exclusion of these researchers from glaciology. The lack of diversity also means that decisionmaking and organization within the scientific community are not inclusive, making community consensus on research priorities more difficult. The glaciology community must actively participate in emerging initiatives that are promoting equity in the geosciences, such as URGE (Unlearning Racism in Geoscience) and Polar Impact, and institutions and funders should reinforce the necessity of self-education about cultural issues in science across career levels, including for established scientists.

There has been a hiring boom in glaciology within the past half decade in the United States, indicating that academia recognizes the field as an important research area. However, this hiring boom is concentrated in a relatively small number of institutions, with many U.S. universities still lacking research on the cryosphere entirely. Further, an emphasis on the cryosphere has not yet been integrated into undergraduate geoscience curricula uniformly, obscuring the discipline's importance for many emerging scientists. Together with a lack of diversity, this lack of exposure translates into fewer students pursuing cryosphere science than are needed, inequitable representation in the research workforce, and generally less understanding of the importance of Earth's cryosphere among the public.

Glaciology suffers cultural shortcomings common across the geosciences, specifically a historic and ongoing lack of gender, ethnic, and racial diversity.

Progress in glaciology also suffers from insufficient funding from federal science agencies. Federal funding for non-defense-related research and development overall dropped from 5.8% of the federal budget in 1966 to 1.5% in 2019. And no U.S. science agency funds long-term (5+ years) glacier or ice sheet investigations except the U.S. Geological Survey (USGS), via its Benchmark Glacier Project, which has been funded since 1958 by a patchwork of USGS grants.

Within the National Science Foundation (NSF), glaciology has no home outside of the Office of Polar Programs (OPP), in contrast to other fields like atmospheric sciences, oceanography, and Earth sciences that are supported by OPP and other programs. NSF therefore lacks the capacity to fund science on midlatitude and tropical glaciers that lie between 60°N and 60°S latitude. Furthermore, in the past 5 years, funding for OPP has dipped to less than 6% (<$500 million) of the total NSF research budget (see Figure 2 online), and only one third of the OPP budget goes to research because of the high costs of supporting polar logistics. This limited amount is then spread across all 10 disciplines working in the polar regions. Assuming an equal split across all 10, the maximum annual amount that glaciology could receive is approximately $10 million, about 10% of the average cost of a U.S. blockbuster movie. Available funding data from NASA are more limited, yet there has been a proportional decrease there as well: Funding for Earth science research, which includes cryosphere studies, dropped from nearly 10% of the total NASA budget in 2017 to 8.5% in 2021.

The shortage of funding for glaciology hurts the United States' ability to prepare adequately for coming changes in water availability for hydropower and general use from vital western U.S. and Alaska glaciers. Further, no coordinating federal body has a sufficient budget, schedule, or scope to focus glaciological research on reducing uncertainty in future sea level projections. The only fed-

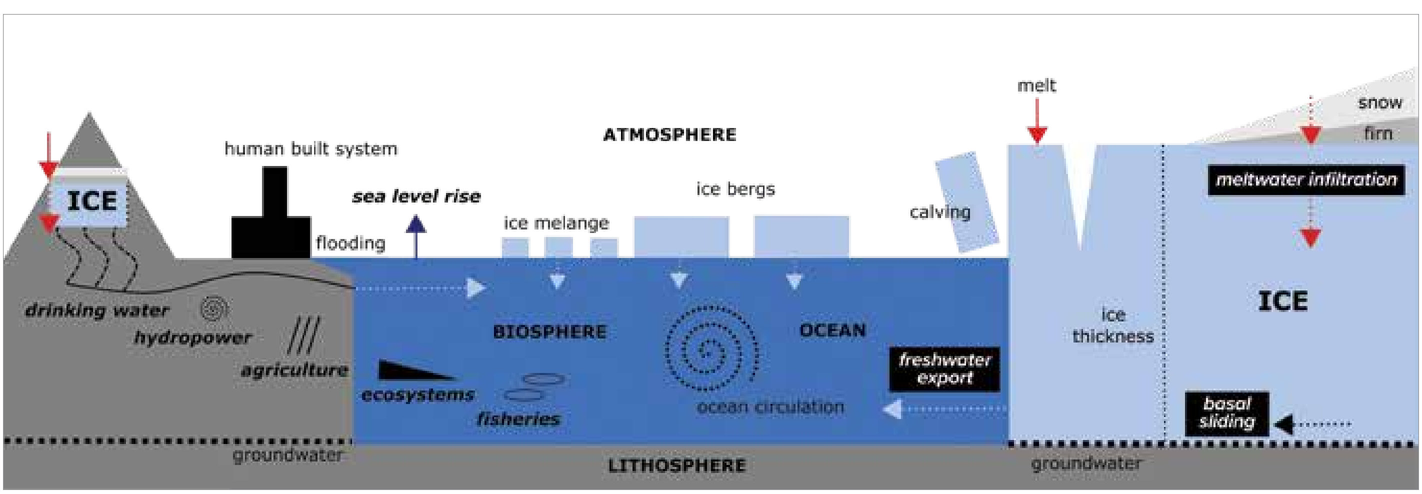


Fig. 1. Gaps in our understanding of glacier and ice sheet systems, including basal sliding, freshwater export, and meltwater infiltration, are represented by dotted lines and occur where different Earth systems intersect and interact. Credit: Caitlyn Florentine, adapted from a webinar given by NSF's Interagency Arctic Research Policy Committee, Glaciers and Sea Level Collaboration Team

erally funded program dedicated to studying sea level is NASA's Sea Level Change Team, which means that scientific problems outside NASA's domain of expertise are researched ad hoc. Such investigations are driven and prioritized by the interest and funding of individual principal investigators rather than by needs identified through research coordination.

Working Together to Build Resilience

The study of our changing glaciers and ice sheets is a critical part of the tapestry of geoscience solutions needed to address 21st century problems like sea level change. Unfortunately, social and organizational shortcomings, along with the low prioritization of funding for glaciology in the United States, have left enormous knowledge gaps, making it much more difficult for scientists to provide the best possible projections of ice loss and local-scale impacts to decisionmakers responsible for planning responses to these problems.

We envision improved cross-agency organization and funding leading to a more comprehensive understanding of glacial processes and ice loss across the entire globe. Although cryosphere researchers gather to present research at many annual venues, we rarely meet to discuss future research priorities. Given the current funding landscape, we propose holding regular, open discussions to facilitate deeper reflection on the critical research needed. Within these meetings, glaciologists must debate, decide on, and then disseminate near- and long-term research priorities for funding that focus on vital observational, knowledge, and modeling gaps. These priorities should include long-term programs to monitor the climate conditions affecting ice sheets, observational programs aimed at improving our understanding of outlet glacier terminus and basal processes, and intensified ice sheet model development to integrate these observational efforts.

We also argue for additional funding for glaciological research. Purposeful, successful investments in such work, scaled to match the high stakes of rising sea levels and other consequences of ice loss, are possible. NASA's recently completed airborne mission Operation IceBridge is one example of how such investment can yield significant results. IceBridge spanned the observational gap between the ICESat (2003–2009) and ICESat-2 (launched in 2018) satellite missions to survey Earth's rapidly changing icescapes across the Arctic and Antarctic [*MacGregor et al.*, 2021]. New data collected during IceBridge revolutionized understanding of ice sheet behavior and provided necessary data on ice volume loss. Another example is the International Thwaites Glacier Collaboration, which has provided collaborative international funding and logistical support to investigate one of the most difficult to study and highly changeable parts of Antarctica.

Reducing resource scarcity and improving cross-agency organization can accelerate a shift from competitive, isolationist tendencies to collaborative work that promotes rapid progress toward filling glaciological knowledge gaps. Glaciologists are largely siloed within their universities, and the current funding environment incentivizes them to remain siloed to protect their research and gain an edge in the hypercompetitive grant proposal arena. More funding opportunities would reduce this competition and the incentives to operate alone. Cross-agency funding initiatives—involving NASA, NSF, NOAA, USGS, the Army Corps of Engineers, and the Department of Defense—focused on sea level science are needed to

- motivate collaboration among glaciologists and between glaciologists and researchers in other disciplines,
- provide critical support for observational studies, monitoring, and modeling of ice sheets and coastal change, and
- support coordination between sea level scientists and policy specialists and others in government, nongovernment, and industry organizations who are knowledgeable about how to apply sea level science for societal concerns [*Ultee et al.*, 2018].

No coordinating federal body has a sufficient budget, schedule, or scope to focus glaciological research on reducing uncertainty in future sea level projections.

Glaciologists dedicate their careers to advancing understanding of the physical processes controlling glaciers and ice sheets—work that vitally informs projections of sea level as well as other potential impacts of ice loss on ecosystems and human well-being. With improved organization and increased financial resources, current research and monitoring can seed expanded efforts that will help the United States fill significant gaps in scientific understanding and build resilience to the consequences of ice loss for the entire world.

Acknowledgments

We thank the members of the glaciology research community who agreed with the opinions expressed in this article by signing their names to the list at this webpage: bit.ly/glacial-knowledge. We also thank Caitlyn Florentine for initiating the conversation and being part of the many helpful discussions that led to the publication of this article.

References

Aschwanden, A., et al. (2021), A roadmap towards credible projections of ice sheet contribution to sea level, *Cryosphere*, *15*, 5,705–5,715, https://doi.org/10.5194/tc-15-5705-2021.

Bernard, R. E., and E. H. G. Cooperdock (2018), No progress on diversity in 40 years, *Nat. Geosci.*, *11*, 292–295, https://doi.org/10.1038/s41561-018-0116-6.

Catania, G. A., et al. (2020), Future evolution of Greenland's marine-terminating outlet glaciers, *J. Geophys. Res. Earth Surf.*, *125*(2), e2018JF004873, https://doi.org/10.1029/2018JF004873.

Dutt, K. (2020), Race and racism in the geosciences, *Nat. Geosci.*, *13*, 2–3, https://doi.org/10.1038/s41561-019-0519-z.

Hock, R., J. K. Hutchings, and M. Lehning (2017), Grand challenges in cryospheric sciences: Toward better predictability of glaciers, snow and sea ice, *Front. Earth Sci.*, *5*, 64, https://doi.org10.3389/feart.2017.00064.

Huss, M., et al. (2017), Toward mountains without permanent snow and ice, *Earth's Future*, *5*(5), 418–435, https://doi.org/10.1002/2016EF000514.

MacGregor, J. A., et al. (2021), The scientific legacy of NASA's Operation IceBridge, *Rev. Geophys.*, *59*(2), e2020RG000712, https://doi.org/10.1029/2020RG000712.

Neumann, J. E., et al. (2015), Joint effects of storm surge and sea-level rise on US coasts: New economic estimates of impacts, adaptation, and benefits of mitigation policy, *Clim. Change*, *129*, 337–349, https://doi.org/10.1007/s10584-014-1304-z.

Noble, T. L., et al. (2020), The sensitivity of the Antarctic ice sheet to a changing climate: Past, present, and future, *Rev. Geophys.*, *58*(4), e2019RG000663, https://doi.org/10.1029/2019RG000663.

Pitman, K. J., et al. (2021), Glacier retreat creating new Pacific salmon habitat in western North America, *Nat. Commun.*, *12*, 6816, https://doi.org/10.1038/s41467-021-26897-2.

Straneo, F., et al. (2019), The case for a sustained Greenland Ice Sheet–Ocean Observing System (GrIOOS), *Front. Mar. Sci.*, *6*, 138, https://doi.org/10.3389/fmars.2019.00138.

Ultee, L., et al. (2018), From ice sheets to main streets: Intermediaries connect climate scientists to coastal adaptation, *Earth's Future*, *6*(3), 299–304, https://doi.org/10.1002/2018EF000827.

Wing, O. E. J., et al. (2022), Inequitable patterns of US flood risk in the Anthropocene, *Nat. Clim. Change*, *12*, 156–162, https://doi.org/10.1038/s41558-021-01265-6.

By **Ginny Catania** (gcatania@ig.utexas.edu), University of Texas at Austin; **Twila Moon,** University of Colorado Boulder; and **Andy Aschwanden,** University of Alaska Fairbanks

▶ Read the article at bit.ly/Eos-glacial knowledge

change IS THE ONLY constant

There's no one way to be a geoscientist. Learn how more than a dozen professionals use Earth and space sciences as a wheelhouse for innovative and interesting careers.

Earth and space sciences offer a stable wheelhouse from which to turn in dizzying directions.

Want to work with both Traditional Knowledges and the Intergovernmental Panel on Climate Change in the Arctic? Turn to the cryosphere (and go fishing).

Want to spend your winter at the South Pole? Turn to geophysics (and know how to grease a telescope in sub-zero temperatures).

Want to be an astronaut? Turn to geology (and brush up on your HTML).

Want to help those suffering from seasonal allergies? Take a deep breath, and turn from atmospheric science to geohealth.

Read on to meet 16 scientists who are redefining both geoscience career paths and approaches to them—geoscience as a vehicle for a "just transition" to clean energy, as a brake on the avian escalator to extinction, as an integration of planetary protection and next-gen education, and more besides.

We are grateful to these scientists for sharing their stories with us and hope they can provide some answers to "What can you do with *that* degree?" questions. They might also inspire you to think about the wheelhouse of your own career and where you can turn next. Either way, please enjoy this special careers feature.

—The Editors

Arch88 / DepositPhotos

FERNANDO TEMPRANO-COLETO

Going with the Flow

A career in fluid mechanics is both intellectually stimulating and well suited to solving environmental problems.

Fernando Temprano-Coleto has always loved machines. As a child, he was fascinated by cars and engines, and he envisioned himself becoming an engineer for a private company. He began a bachelor's degree in engineering at the Universidad Politécnica de Madrid with this career in mind, but a summer internship changed his path.

The internship was at Harvard University, where Temprano-Coleto worked on modeling the origin of life without biochemical building blocks like DNA and amino acids. Almost immediately, he fell in love with the careful thinking and continuous learning that characterizes academic research. "That's when I knew that I wanted to do a Ph.D. and I was going to go into research," he said.

"It's really nice to be working on something that can eventually have a real effect on the world."

The internship also left Temprano-Coleto with an interest in combining fluid mechanics and chemistry. Later, as a Ph.D. student at the University of California, Santa Barbara, he explored this interface by studying molecules called surfactants, which lower the surface tension between liquids. Surfactants have practical applications (like making boats glide smoothly to reduce fuel consumption), but Temprano-Coleto's most popular experiment was more whimsical. He and his colleagues made a video showing how surfactant chemistry allows soap to solve a maze. The video landed him a spot on the Spanish TV show *El Hormiguero*, which often features interviews about wow-factor science.

Temprano-Coleto has said intellectual curiosity drives his work, but he also appreciates the environmental applications that often come out of fluid mechanics research. Now, as a postdoctoral fellow at Princeton University, he's using concentration gradients of charged particles to separate microplastics from water. This technology might one day allow water treatment facilities to remove microplastics before returning water to the environment—something that's prohibitively expensive using traditional filters. "It's really nice to be working on something that can eventually have a real effect on the world," he said.

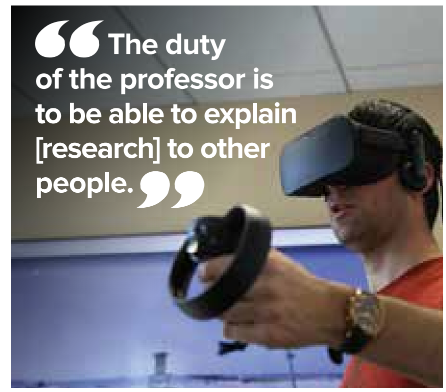
—**Saima May Sidik** (@saimamaysidik), Science Writer

ALEXANDRE MARTINEZ

The Virtual Reality of Climate Change

Martinez brings science to the public using technologies like virtual reality to improve understanding of climate change.

Alexandre Martinez didn't plan to become a climate data scientist and modeler. While growing up in the French countryside, he took an early interest in mathematics and philosophy, and he got his engineering degree at École Centrale de Lille. When Martinez was trying to decide what his next step would be, his English professor recommended he apply to a graduate program in the United States. "So I said, 'Why not?' It was a new adventure for me."



Alexandre Martinez, wearing virtual reality equipment, hopes to use VR to engage the public in local climate change policy. Credit: Alexandre Martinez

Martinez was able to work on a variety of environmental projects as he pursued his environmental and water resources engineering master's degree at the University of Texas at Austin and his Ph.D. in civil engineering at the University of California, Irvine. During his Ph.D. he focused on forecasting hydrologic disasters and mitigating their effects on food production and the supply chain. But he quickly realized he wasn't content to work at the pace of academia, waiting years for his work to affect society.

So Martinez partnered with a friend, a graphic design professor at San Jose State University, to create The Climate VR, a virtual reality tool that projects climate scenarios onto surrounding walls and ceilings. With this tool, users can see for themselves how sea level rise will affect their community and how a seawall might prevent flooding. "What we want to do is to use this tool to improve the communication between citizens and centralized institutions," said Martinez.

His desire to apply his research also led him to apply to AGU's 2020–2021 Voices for Science cohort to improve his science communication skills. "If we are Ph.D. students and we want to be professors, the duty of the professor is to be able to explain [research] to other people," said Martinez. If you can't explain your research to nonscientists, he said, having a Ph.D. isn't very useful.

Martinez graduated in 2021 and now works on exposure modeling of marine cargo at Risk Management Solutions. Eventually, he wants to become a professor to show future students how to carry out research for the benefit of others.

—**Jackie Rocheleau** (@JackieRocheleau), Science Writer

Freya Garry sailed on RRS James Clark Ross *to Antarctica during graduate school. Her research focused on different sampling strategies in the deep ocean and how they affect models. Credit: Freya Garry*

FREYA GARRY

Forwarding Knowledge on Climate and Gender

A climate scientist builds a network for women and nonbinary people in her field.

Whether it be about climate or gender issues, Freya Garry wants you to have the information you need.

As a climate scientist at the U.K.'s Met Office, Garry interprets the projections of Met Office climate models for federal agencies and industrial sectors. She also cofounded the Women in Climate network, a community-led group, to advance gender equity in science.

Garry grew up on the rugged coastline of the Isle of Man, an island between Great Britain and Ireland. Her parents owned a dry cleaning shop and often took her canoeing on lakes and rivers. In her late teens, she scuba-dived frequently, seeing lobsters, eels, and basking sharks. Garry noted that she attended publicly funded schools. "A lot of people in science that I've encountered went to private schools and come from well-off families," she said. "It is important to me to highlight that I did not have that schooling, to help encourage people from lower socioeconomic backgrounds to pursue science as a career."

After completing high school, she worked in financial administration, eyeing college degrees. She also volunteered at a primary school near Arusha, Tanzania, teaching math, English, and science. "My experiences there, seeing how different life is for so many people in this world, have really influenced my understanding of the impacts that climate change will have for the Global South," Garry said.

Her love of the ocean and interest in climate change led to an integrated master's (a 4-year program that combines undergraduate and graduate courses) in oceanography at the University of Southampton. She stayed on for a doctoral degree in oceanography, and that's when her ties to the Met Office, the United Kingdom's national weather service, began. The agency funded part of her degree, and soon after finishing it, she headed to the Met Office's home city for a postdoctoral position at the University of Exeter.

By then, Garry had grown tired of surface-level discussions of gender and science, so she and friend Penelope Maher launched the Women in Climate network. The network hosts book clubs, career talks by established scientists, and workshops (on tools like comedy for climate communication) aimed at women, nonbinary people, and men.

Around this time, Garry considered what to do after her postdoc. Met Office jobs pay less than university positions, she said, but they don't require early-career scientists to move around. The agency also offers scientists a permanent job instead of a temporary post, ample holiday leave, and a strong focus on work-life balance and well-being. For these reasons, she took the leap and enjoys this role, where she wears many hats. Recently, for instance, she spoke virtually to an agronomy conference to discuss climate's effects on U.K. agriculture.
—**Jenessa Duncombe** (@jrdscience), Staff Writer

SIAN PROCTOR

Community College Professor Goes to Space

An Arizona educator finds she has the SpaceX factor to become an astronaut.

In 2021, geoscientist, explorer, and community college professor Sian Proctor became the first Black woman to pilot a spacecraft as part of the SpaceX Inspiration4 all-civilian crew.

As a child growing up throughout the northeastern United States, Proctor wondered what created the landscapes around her while also dreaming of flying F-16s and going to space. Though her need for glasses thwarted her fighter pilot ambitions, Proctor's parents—neither of whom had college degrees—instilled in her the idea that education would change her life.

After obtaining an undergraduate degree in environmental science and working as a video editor, Proctor saw graduate school as a way to move West and reconnect with science. Arizona State University (ASU) recognized her potential: "I got out-of-state tuition waived, and then they made me a TA, because I had no money. And that changed everything."

"I packed up my black hardtop Jeep Wrangler," she remembered, "and with no air-conditioning, from upstate New York, drove across country."

For her master's thesis, Proctor combined geosciences and education, causing controversy at the time. She received anonymous notes in her mailbox telling her she didn't belong because her thesis was not focused purely on geology. (ASU now has an entire science education program.) She recalled how one professor watched her successfully construct a geologic map in the field, telling her, "I didn't think you were going to make it until I saw you map."

For her doctoral studies, Proctor continued exploring visual-spatial learning in the education department at ASU while simultaneously teaching geology full-time at a local community college. Throughout her Ph.D. work, she dodged negative comments denigrating community college as a career choice—nearly quitting her degree in frustration. Determination, grit, and a mentor, Sarah Brem, helped Proctor cross the finish line. "I would not be Dr. Proctor if it wasn't for her," she said.

A friend prodded Proctor to apply for NASA's 2009 astronaut class, for which she had nearly every qualification—Ph.D., pilot's license, scuba certification—except speaking Russian. Proctor's own inner voice would discourage her, saying, "They're never going to select you"—but she made it to the final 47 (out of more than 3,500 applicants) before being cut.

Her string of near successes continued. In 2012, Proctor auditioned to be the host of a children's television show—a dream job. She didn't get the gig. After the untimely death of the first host, Proctor reauditioned, losing yet again. "As a woman of color, getting your own TV show is so hard," she said, recounting how directors at the time told her, "You're amazing, but the U.S. won't take a Black female lead."

But Proctor persevered, becoming an analog astronaut at a simulation site in Hawaii, making television appearances, and traveling extensively—until COVID-19 kept her close to home. "I became a space artist and poet," she said.

Meanwhile, Inspiration4 was searching for a crew representing the mission pillars of leadership, hope, generosity, and prosperity. Proctor applied, and her poetry and online art shop helped her land the "prosperity" seat on the crew.

Sian Proctor stands in her astronaut gear shortly after Crew Dragon's splashdown. Credit: SpaceX, CC BY-NC 2.0 (bit.ly/ccbync2-0)

On 15 September 2021, the Crew Dragon space capsule launched Proctor and her three crewmates into orbit. As she peered at Earth from the spacecraft's cupola, earthlight bathed her skin. "It was the best perspective I could ever imagine," she said.

Today Proctor is the astronaut in residence for the Maricopa County Community College District in Arizona, and though she no longer teaches, she consults on questions about the future of education while plotting her next adventure. "I'm an explorer at heart," she said. "That's my foundation."

You can follow Proctor's adventures on social media @DrSianProctor.

—Alka Tripathy-Lang (@DrAlkaTrip), Science Writer

SANDEEP PAI

A *Just Transition* to Clean Energy

Making sure people whose incomes rely on fossil fuels aren't left behind as alternative energy sources become more established.

When Sandeep Pai was finishing high school in rural India in the early 2000s, conventional wisdom held that two professions offered a good living: medicine and engineering. Choosing to be an engineer, Pai earned a bachelor's degree in computer science. But programming never really spoke to him. Instead, he enjoyed writing, politics, and public policy.

So Pai became a journalist. "It was a big leap," he said. After earning a journalism diploma, he landed a job with a prominent Indian news network. Few journalists knew computer science at the time, and Pai found that his data analysis skills were valuable to investigative reporting.

VASHAN WRIGHT

A Champion for DEI in the Geosciences

While studying tectonic plates and sand, Wright works on a program to make the geosciences more equitable.

Vashan Wright's work brought him from his home in Jamaica (where he studied the Enriquillo-Plantain Garden Fault) to Botswana (where he studied the birth of the Okavango rift) and even to Mars (where he's studying the seismic properties of subsurface ice). Today Wright is an assistant professor at the Scripps Institution of Oceanography and a guest investigator at Woods Hole Oceanographic Institution, where he focuses on how tectonic plates, fluid flow, and climate change affect granular media like sand.

Credit: Pablo Canales

Wright was part of a team that created 3D structural images of laboratory and natural sand grains to determine the differences between the two. The researchers discovered that natural sand is more stable and harder because its structure has been rearranged by waves to have a strong horizontal orientation. Wright has expanded his study of sand to the Red Planet, using data from the NASA InSight lander's seismometer to shed light on what is under the surface of Mars.

Wright is also the founder of Unlearning Racism in Geoscience (URGE), a program that aims to make the geosciences—one of the least diverse fields in science, technology, engineering, and mathematics (STEM)—more just and diverse. During the first 4 months of 2021, Wright worked with the URGE leadership team to support more than 4,000 geoscientists in 312 groups (pods) from different laboratories, universities, and government agencies. On the basis of URGE-provided journal articles, interviews with experts, and videos about racism, participants discussed inclusivity and the best ways to navigate challenges to diversity, equity, and inclusion in the workplace. The pods also helped draft anti-racist policies for their workplaces.

"We were updating a strategic plan for enhancement of diversity…and many of our deliverables were translated into that," said Michael Manga, leader of the URGE pod at the University of California, Berkeley.

The URGE team is continuing to assess the material submitted by the pods, and Wright is looking forward to its ongoing work in assessing the challenges of implementing antiracist policies. "I'm really excited to hear from institutional leaders," said Wright, who is also interested in thinking about how URGE members can effectively communicate with colleges that have not participated in the program.

"URGE is a part of my science—it's [ongoing] research," Wright concluded.

—Santiago Flórez (@rflorezsantiago), Science Writer

Pai enjoyed journalism, but he eventually tired of transitioning quickly from one topic to the next. He decided to earn a master's degree in environmental sciences, policy, and management to narrow the scope of his work. During the program, he began to think about the many communities, from India to the United States, where fossil fuels provide a critical source of income. Phasing out fossil fuels is necessary to combat climate change, but the transition will be difficult in these places because "the whole ecosystem gets disturbed," Pai said.

Pai and classmate Savannah Carr-Wilson, whom Pai eventually married, spent a summer traveling to communities that depend on fossil fuels and writing a book called *Total Transition: The Human Side of the Renewable Energy Revolution* based on what they learned. The couple realized that the term "just transition"—which the labor movement uses to describe the process of minimizing harm to people who depend on old ways of life as new ways take hold—applies to the switch to clean energy.

Pai later performed foundational work on just transition as a Ph.D. student at the University of British Columbia. Today he's a senior research lead for the Global Just Transition Network at the Center for Strategic and International Studies. This new network is currently focused on helping communities in three countries—India, South Africa, and the United States—phase out coal. One of Pai's goals is to foster communication between these communities so they can compare strategies for economic recovery and environmental remediation and learn from each other.

Sandeep Pai (left) interviews a third-generation coal worker who lives in the mining community of Jharia in the Indian state of Jharkhand. Credit: Parwaz Khan

Pai's work with the Global Just Transition Network is "the next logical thing," he said. After spending years in the research realm, he's excited to engage with policymakers to "make this research useful and take some action."

Follow Pai on Twitter @Sandeeppaii or his podcast, *The India Energy Hour.*

—Saima May Sidik (@saimamaysidik), Science Writer

Emil Cherrington stands on a boat in the middle of a river in Belize in May 2019. Credit: Emil Cherrington

EMIL CHERRINGTON

Bringing Satellite Data Down to Earth

Showing how eyes in the sky can help people on the ground.

Emil Cherrington was born in Belize at a time when there were few opportunities to pursue a science education in his country.

"When I was younger, I didn't see many role models actively doing science, and so it was difficult for me to see how I could practice science in Belize," Cherrington said. "I wanted to study science, but I wasn't sure what would come after studying science, which itself at times felt like a pipe dream."

When he was young, four of his mother's seven siblings had pursued higher education in the United States. "In addition to my parents' encouragement…their example also helped light the way for me," Cherrington said. He recalled that his Aunt Carolyn was the first of his mother's siblings to study abroad—she earned degrees in

MICHAEL KOTUTWA JOHNSON

A Voice for Indigenous Agriculture

A farmer draws on Traditional Knowledges to restore the Native American food system.

When Michael Kotutwa Johnson walks through his fields on the Hopi Reservation, he sings to the corn, beans, and melons to help them grow healthy and strong. "It's an intimate relationship Hopi farmers have with their crops," Johnson said. "We think of them like family."

At the age of 8, Johnson began learning from his grandfather how to grow crops without irrigation on the semiarid high plateaus of northeastern Arizona. Then, as a teenager with a strong bass-baritone voice, he went to Arizona State University to study vocal performance. Johnson struggled with the curriculum, however, and eventually returned home to his first love: farming.

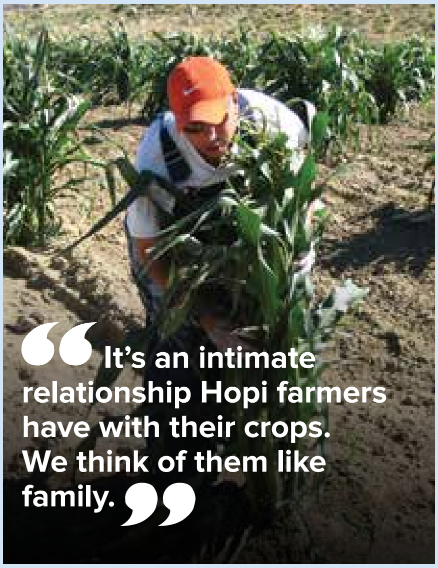
Johnson then went to Cornell University in New York, where he majored in conventional agriculture. It was there he realized the value of Native American agricultural practices, such as planting seeds up to 45 centimeters (18 inches) deep to make full use of the moisture below, and following an agricultural calendar based on regional weather patterns. Johnson recognized that such time-tested techniques have provided food and resources to communities in a way that has sustained the environment. "If you look back for millennia, Indigenous People have been stewarding the land very well with their practices," Johnson said.

Johnson also realized that as a result of a variety of factors, many Native American tribes could no longer farm, hunt, or gather as they had done for centuries—to the detriment of their food sovereignty, their health, and the environment. He knew that to address this challenge, he'd need a place at the policymaking table, and he went on to study for a Ph.D. in natural resources and conservation at the University of Arizona in Tucson.

Throughout his Ph.D. studies, Johnson continued to raise crops as a Hopi dryland farmer. He still does, but now his mission is broader than keeping cultural traditions alive and protecting the land that has fed his tribe for millennia. His focus is on pushing restoration of the American Indian food system based on the ideas of Indigenous conservation and stewardship.

In May 2022, Johnson joined the faculty at the University of Arizona's School of Natural Resources and the Environment. He will also be part of the university's Indigenous Resilience Center, where he hopes to use his experience as a farmer, his training in policy, and, most of all, his strong voice for change.

—Jane Palmer (@JanePalmerComms), Science Writer



Hopi farmer Michael Kotutwa Johnson tends corn on his northern Arizona farm. Credit: Michael Johnson chemistry and biology and later a master's in education—and had sparked his interest in science at an early age. "My aunt gave me my first computer—secondhand—an encyclopedia set, and a host of science books," he said. "She encouraged me to study science, and I remember as a child, she would listen patiently to my questions about how things worked."

He followed in his relatives' footpaths and pursued higher education outside Belize, first studying biology at Loyola University Maryland in Baltimore and then earning a master's in forest resources at the University of Washington (UW) in Seattle.

At UW, Cherrington's research into the United States and Belize's 2001 "debt-for-nature swap" was his first exposure to how Earth observation satellites can provide critical information that aids people on the ground and can also hold governments accountable to their environmental pledges.

Cherrington's research brought him back to Belize as part of government environmental agencies and then led him to Panama to work for the Water Center for the Humid Tropics of Latin America and the Caribbean. In November 2006 and November 2008, he presented satellite images that tracked the severity of ongoing flooding in Panama to the then president and vice president of the country. Recommendations based on those images were used to inform nationwide alerts. "It was the first time that I had ever seen such high-level decisionmakers requesting satellite-derived information, and it left an impact on me," he said. "It was impressive to see that the information we had provided was used to take concrete actions to try to protect life and property."

After working outside academia for 9 years, Cherrington decided to pursue a joint Ph.D. in ecology and forest resources at AgroParisTech in France and the Technische Universität Dresden in Germany. "My entire university education was financed by scholarships," he said. "I consider myself extremely lucky to have gotten these scholarships, and at the same time I've also felt guilt because I know that there are so many deserving students and relatively few opportunities."

Cherrington is currently a research scientist at the Earth System Science Center at the University of Alabama in Huntsville and also serves as the regional science coordination lead for West Africa for the SERVIR program, a joint initiative of NASA, the U.S. Agency for International Development, and regional geospatial organizations around the world. The research agency Cherrington worked for in Panama was the first SERVIR global hub, so he has been working to bring critical satellite-based geospatial information to global communities for nearly 16 years.

"When I was in high school, I was told by some of my peers that I'd never get a scholarship to study abroad or that I was dreaming too big, because of my family's modest means," he said. "I hope that future generations—and fellow scientists—feel free to follow their dreams, in spite of the occasional naysayers."

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

BENJAMIN FREEMAN

Slowing Birds' "Escalator to Extinction"

From Bolivia to Peru, Freeman researches how a warming world affects tropical birds.

Ben Freeman holds a collared trogon in the Cerro de Pantiacolla in Peru as part of his research studying how climate change affects birds. Credit: Graham Montgomery

While he was an undergraduate student at Macalester College, in St. Paul, Minn. Ben Freeman took a semester off to travel to Bolivia to work as a field assistant on a project that studied the migratory behavior of tropical birds, like the tropical kingbird. The immersive experience of collecting data, tracking individual birds, and making behavioral observations left Freeman hooked on field biology.

"It just blew my mind.... There are more species in 5 kilometers around where I was staying than there are in the entirety of North America," he said.

Freeman went on to work as a bird guide in Colombia, and he became enamored of why different species live where they do. Among other factors, he saw climate change become a prominent reason for birds' residence and change in habitat. In mountainous regions, climate change causes species to move uphill to escape warming temperatures, like they are riding an escalator, Freeman said. "But then for species that live at the top of the mountain, they have nowhere higher to move up to. So, for them, it's an escalator to extinction."

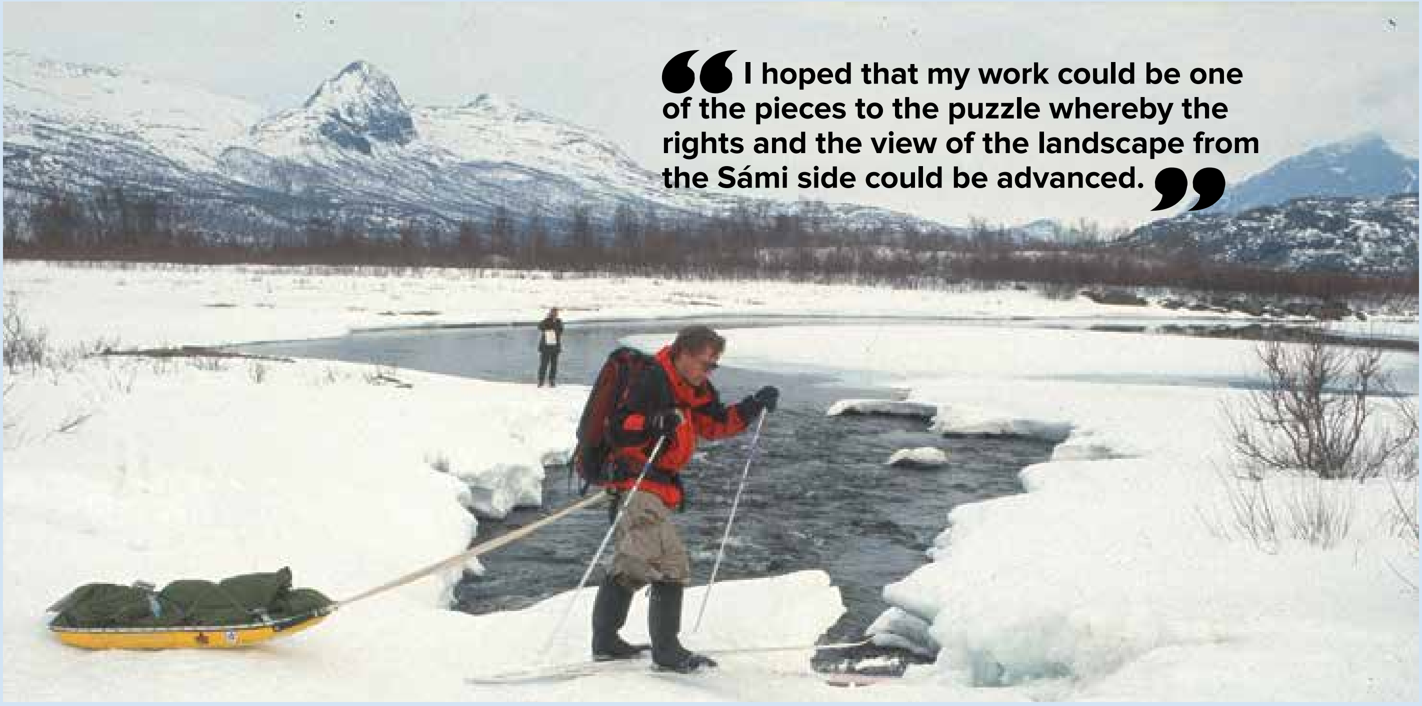
In one 2018 study, Freeman and colleagues discovered that this escalator is already running out in Peru. Returning to the same mountain ridge, Cerro de Pantiacolla, that his graduate school adviser, John Fitzpatrick had surveyed in 1985, Freeman and other scientists resurveyed the tropical bird species in the area, including the scarlet-breasted fruiteater. There were fewer birds at the ridgetop, and of the 16 bird species that previously lived at high altitudes, the researchers were unable to account for eight of them.

These findings prove that climate change is happening now and isn't just a future worry. The escalator to extinction is "something that's already happened in my lifetime," said Freeman, now a postdoctoral fellow at the University of British Columbia in Canada.

Although there are ways to predict climate change's impact on bird species, Freeman believes fieldwork is imperative. "We need to go out in the field and see what's happening as a way both to understand what's happening in nature and to understand whether we can believe these model predictions or whether we need to revise those models," he said.

"The future that I want personally to live in is a future world that has as much of Earth's biodiversity as possible," Freeman said.

—Richard Sima (@richardsima), Science Writer



Tero Mustonen skis in Sarek National Park in Sweden on a fieldwork assignment. Credit: Tero Mustonen collection

TERO MUSTONEN

Disrupting the Status Quo

Advocating for the importance of Traditional Knowledges in Finland and beyond.

Tero Mustonen never set out to be a scientist. His first job after high school was as a wilderness guide, and he spent several years exploring his native country of Finland, as well as Canada and the United States. As a guide immersed in the natural world, he encountered Indigenous Peoples who also lived in close connection with the land: the Sámi in Finland, Native Americans in the United States, and First Nations groups of Canada.

Mustonen soon noticed that these groups, with their extensive environmental knowledge, were often left out of the decisionmaking process when it came to managing the lands they lived on. To draw attention to the value of the environmental knowledge that Indigenous Peoples have of their land and to argue for social justice for marginalized Indigenous communities, Mustonen enrolled in an undergraduate and then a master's program in international relations at the University of Tampere in Finland.

"At the time, there was this notion of social justice and passion that you can change the world," Mustonen said. "I hoped that my work could be one of the pieces to the puzzle whereby the rights and the view of the landscape from the Sámi side could be advanced." But in the 1990s, there was little academic consideration given to how human societies engage with the landscape and ecosystems.

Continuing into his Ph.D. program, Mustonen investigated and documented the deep and rich "endemic" knowledge that three communities—the Kesälahti in Finland and the Iyengra and Lower Kolyma of Sakha-Yakutia in Russia—hold about the environments they live in. In his thesis, Mustonen argued that such endemic knowledge, or Traditional Knowledges, is equally as valid as Western science when it comes to understanding and caring for the environment. "My argument caused a riot in the entire department," Mustonen said.

But despite being viewed as a disrupter during his studies, Mustonen believes that integrating Western science and Traditional Knowledges is critical because both provide value in complementary ways. For example, he points out that Indigenous and local communities don't have solutions to problems such as radioactive, acidic, or biochemical pollution, whereas Western science can help address these issues. Alternatively, Indigenous communities have centuries of experience in how to live sustainably in their natural environments and protect food and water for future generations. The difference is that Indigenous Peoples' knowledge isn't always valued the same way as Western science, Mustonen said.

Therefore, arguing for respect and Indigenous Peoples' rights has been the common theme of Mustonen's career ever since. In 2000, he cofounded the nonprofit Snowchange Cooperative, which works with local and Indigenous communities in the northern regions of Finland, including the Sámi, Chukchi, Yukaghir, Inuit, and Inuvialuit.

Currently, Mustonen is president of Snowchange, and he is also head of the village of Selkie, North Karelia, Finland; a professional fisherman; and an adjunct professor in the Department of Geographical and Historical Studies at the University of Eastern Finland. In 2018, he was appointed as a lead author for the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In this role, he has been able to advance the contributions to the report of Indigenous and local Traditional Knowledges that are in peer-reviewed literature.

In his career, Mustonen has come to find that "science is not good or bad. It's a way of assessing, communicating, and deducting, just like Traditional Knowledge is." He added that "if you use both [Traditional Knowledges and Western science] well, you can get to a really exciting place."

—Jane Palmer (@JanePalmerComms), Science Writer

FIONA LO

A "Really Long, Convoluted Path" to Health

Lo uses her background in atmospheric sciences to forecast pollen concentrations.

Twenty years after getting her master's, Fiona Lo returned to graduate school to work on her Ph.D. thesis, which she presented at the American Meteorological Society annual conference in 2018. Credit: Fiona Lo

Just like 60 million other people in the United States, Fiona Lo suffers from allergies. Having an interest in human health, she thought, "Well, I have allergies, what would help me?"

Lo uses her atmospheric science training to produce models that can forecast pollen concentrations. These models can help predict the start of the pollen season as well as particularly high pollen days, which can help determine when people should take allergy medications and how much they need. Her career helps her "do something that will help society," said Lo, now a postdoctoral researcher at the University of Washington.

Yet despite her long-standing interest, her research combining climate and health "came about from a really long, convoluted path," Lo said.

She actually started her academic career focusing on otherworldly systems. Lo completed her undergraduate degree in planetary sciences, and then she applied to graduate school to study atmospheric sciences.

EDGARD RIVERA-VALENTÍN

Boricua Planeteer

Inspired by the science infrastructure in their own backyard.

Edgard Rivera-Valentín (far left) stands with a group of Boricua Planeteers. Credit: Edgard Rivera-Valentín

Growing up with the largest radio telescope in the world in their backyard set Edgard Rivera-Valentín on a path of planetary exploration at an early age.

Rivera-Valentín first visited Arecibo Observatory in Puerto Rico when they were around 5 years old. Their family moved from Arecibo to Pennsylvania when they were still young, "but we still visited every other year to Puerto Rico," Rivera-Valentín said. "Every visit, I made my family take me back to the observatory because it's such an icon. When you're there, it inspires you to do more, to be more. So I always made them take me there, and that kept fueling my passion to do something in science."

After taking a class in planetary science at Alfred University in New York, Rivera-Valentín realized that they wanted to pursue a career in that field—so they worked with the professor of the class to create a new planetary science minor at the university. Rivera-Valentín undertook an internship at the Lunar and Planetary Institute (LPI) in Houston in 2007, where they studied craters on Jupiter's Galilean moons.

After graduating, Rivera-Valentín joined the planetary science Ph.D. program at the University of Arkansas, where they studied the stability and transport of water on Mars and Saturn's moon Iapetus.

Another internship during their graduate studies, this time at NASA Jet Propulsion Laboratory in Pasadena, Calif., gave them experience helping to develop space exploration missions. The network they developed through their two internships led them to a postdoctoral fellowship at Brown University and, after, back to Arecibo.

"I got to work at the observatory for 4 years, which was awesome," they said. "I became the first scientist from the city of Arecibo to get to work at the observatory, and one of the few Puerto Rican scientists ever to work at the observatory. You can count us all on your hands."

"I became the first scientist from the city of Arecibo to get to work at the observatory, and one of the few Puerto Rican scientists ever to work at the observatory."

While at Arecibo, in addition to their planetary radar science research, Rivera-Valentín focused heavily on community engagement and inspiring the students of Puerto Rico to be interested in science. They

"I think I wasn't sure what I wanted to do," she said.

After attaining her master's degree, Lo worked as a research scientist for a slew of organizations—including NorthWest Research Associates and Cornell University, to name a few—but she always wanted to pursue her lifelong love of health. So after 20 years of working as a research scientist, Lo returned to graduate school once more.

"I enjoyed my time in graduate school a lot more the second time because it was driven by my own passion and interest," she said.

While at the University of Washington, she created a machine learning pollen model and researched heat-related illnesses. She graduated with her Ph.D. in atmospheric sciences in 2020.

"It's just good to follow your dream, even if sometimes your dream changes," Lo said.

—Richard Sima (@richardsima), Science Writer

were a project manager for the Arecibo Observatory Space Academy, which provides astronomy research experience to local high school students. "That program was amazing. Over 90% of the students that graduated ended up going to college to do a STEM degree," Rivera-Valentín said.

After Hurricane Maria damaged the observatory and much of the surrounding region in 2017, Rivera-Valentín moved to Houston and continued their planetary defense, protection, and exploration research at LPI.

"One of the things that attracted me to the LPI is that it is a primarily community service institute…you're expected to have at least 30%–50% of your time available to do community service," they said. "I still get to do science, but I also get to help the community out. I still get to help and work with students. It's fulfilling to pursue both of my passions: helping people and doing science." Rivera-Valentín is currently a senior planetary scientist at LPI.

As part of that service, Rivera-Valentín has organized conferences for the planetary science community, including the Advancing IDEA in Planetary Science conference, which took place in April 2022. (IDEA stands for inclusion, diversity, equity, and accessibility.) They also cofounded the Boricua Planeteers, an advocacy group that provides a network for Puerto Rican space and planetary scientists and helps develop those studies in Puerto Rico. You can follow Rivera-Valentín's continuing research and community service projects on Twitter @PlanetTreky.

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

RITA DE CÁSSIA DOS ANJOS

Never Settle for Things as They Are

The award-winning astrophysicist is using her visibility to call attention to inequalities in the Brazilian science community.

In 2020, Rita de Cássia dos Anjos was one of the awardees of the Brazilian edition of the L'Oréal/UNESCO prize for Women in Science, promoted jointly with the Brazilian Academy of Sciences. Credit: Rita de Cássia dos Anjos

"I was always curious as a child. And my mother was my greatest supporter, always reminding me that I shouldn't accept things as they were," said astrophysicist Rita de Cássia dos Anjos, adjunct professor at the Federal University of Paraná (UFPR) in Palotina, Brazil.

As a Black girl from a modest family in Olimpia, northern São Paulo State, the first barrier Cássia dos Anjos could not accept was the gap between the education she received in public school and what she needed to get into higher education. "By the end of high school, my sister managed to pay for a yearlong prep course for university exams, and I noticed that I really lagged behind my peers," she said. Not having been approved in her first attempt, Rita asked the course coordinator if she could attend classes for another 6 months. He allowed it, and that time around, she was approved to study biological physics at Universidade Estadual Paulista Júlio de Mesquita Filho in São Paulo.

"I really looked up to my mother, and she worked as a nurse. So I wanted to study biology but really fell in love with physics during the prep course. So I thought biological physics was the perfect choice," she said.

During the course, however, physics spoke louder, and Cássia dos Anjos answered. She went on to earn a master's degree from the University of São Paulo, studying integrable field theory and solitons, waveforms that keep their shape while traveling.

During her doctorate, also at the University of São Paulo, Cássia dos Anjos studied cosmic rays—atomic particles that cross Earth from beyond the galaxy. To seek out where cosmic ray particles come from, she studied starbursts—extremely luminous galaxies that are source candidates for these particles traveling at almost the speed of light.

Immediately after finishing her doctorate in 2014, Cássia dos Anjos began teaching modern physics at UFPR. Three years later, she was a Fulbright Visiting Scholar at the City University of New York, where she stayed for 3 months. "I was at the Lehman College, Bronx," she said. "The neighborhood looked like the *Everybody Hates Chris* TV show. Everybody there was Black, and I loved it. But at the college, there were fewer Black people…the overwhelming majority of the faculty was white."

These demographics are not very different from many parts of Brazil, she said. "My campus is small, with around 140 faculty members. Up to 2 or 3 years ago, I was the only Black faculty member here. Now there's a pardo [mixed ancestry] professor as well," Cássia dos Anjos said. Even if 70% of the population in Paraná is white, Blacks and other ethnic groups are vastly underrepresented among the higher ranks of academia in Paraná and elsewhere in Brazil.

Cássia dos Anjos has had a larger public presence since her research earned her a Serrapilheira Institute grant in 2018 and a L'Oréal-UNESCO for Women in Science (Brazil) award in 2020. She uses the visibility from her prizes to call attention to inequalities in gender and race that pervade Brazilian science. She's working on funding for projects in which she can work with young girls in science to get them to try their hand at real research. "I feel it's my responsibility as a woman of color to help open the path to other women of color in my field," she said.

—Meghie Rodrigues (@meghier), Science Writer

JIMENA DÍAZ LEIVA

Changing Conservation Narratives

Díaz Leiva has been to Peru and beyond as she works on environmental and social justice projects.

As a second grader in Seattle, Jimena Díaz Leiva remembers being captivated by her teacher, who described football fields' worth of deforestation in the Amazon. Because she was born in Peru, "it was really tangible on an emotional level," said Díaz Leiva. "It was an issue that I became really passionate about."

After college, she accepted a postgraduate research fellowship that allowed her to return to Peru and focus her work on the environment. In the Madre de Dios region, she assisted a freshwater monitoring project in the Amazon with the nonprofit organization Conservación Amazónica–ACCA. Speaking with local people, she learned that conservation initiatives like protected areas and nature preserves can have unintended consequences, such as cutting fishermen off from traditional fishing grounds.

"Those [conservation initiatives] weren't addressing some of the root issues around why there was habitat degradation or environmental degradation broadly" and failed to consider the people living in those areas, she said. Díaz Leiva also learned about the small-scale gold mining nearby, in which miners used mercury to extract gold from sands, which inspired her Ph.D. dissertation.

Díaz Leiva's dissertation challenged conventional narratives of gold miners as bad actors. These common assumptions "fail to get at the complex historical and political processes" that existed before the gold mining expansion and influenced mercury use, she said.

After completing her doctoral work at the University of California, Berkeley in 2021, Díaz Leiva joined the Center for Environmental Health as its science director. There she's designing an air pollution monitoring network for Paramount, Calif., alongside community members, putting into practice some of her environmental and social justice learnings. "It just seemed like the right next stepping-stone," she said, adding that she has been able to help and "to work directly with individuals [who] were experiencing pollution and contamination from industries," she said.

—**Jackie Rocheleau** (@JackieRocheleau), Science Writer

Jimena Díaz Leiva in Yosemite National Park. Credit: Jimena Díaz Leiva

LAUREN HAYGOOD

Normalizing STEM in America's Heartland

Community science builds bridges while generating valuable environmental data.

Oklahoma geoscientist Lauren Haygood takes a field trip to the state's Arbuckle Mountains. Credit: Madison Culver

Today Lauren Haygood is a first-year Ph.D. student at the University of Oklahoma, where she's using deep-sea sediment cores to reconstruct Earth's past climate.

But growing up, Haygood wasn't interested in becoming a scientist. She loved sports and intended to pursue a career in sports medicine. When her family moved from California to Oklahoma the summer before her junior year of high school, two converging events changed her plans.

First, Haygood took a sports medicine class at her new high school. "I absolutely hated the class," she said. Second, she and her mom planted a garden in their new backyard. Haygood was fascinated by how the soil's nutrient composition was reflected in characteristics of the plants. The experience motivated her to earn bachelor's and master's degrees in geosciences from the University of Tulsa.

Haygood plans to become a university professor, so during college she joined AGU's Voices for Science, which she hoped would improve her teaching skills. In the program, participants learn to communicate research to policymakers, journalists, and the public. It left her feeling inspired to get involved in science policy and to help bridge the gaps between scientists, politicians, and the public.

One of the ways Haygood drew on this inspiration was by starting What's in Your Water?, a project in which community scientists analyze local water for contaminants. In addition to filling a gap in Oklahoma's water quality data, "it was also educational," Haygood said. People were "learning about how to properly talk about a water system's health in regard to the toxins."

Sometimes painful stereotypes have cropped up during Haygood's policy work. Once, she said, a member of a politician's staff told her that there was "no point in pursuing a STEM degree because women in Oklahoma just become housewives." She hopes that normalizing scientific careers will alleviate burdens for future generations of scientists, especially minoritized groups. "I want to make the pathway easier for people coming up behind me," she said.

Keep up with Lauren Haygood on Twitter and YouTube @La_U_Re_N.

—**Saima May Sidik** (@saimamaysidik), Science Writer

Allen Foster enjoys the sun while he can, before overwintering to maintain the South Pole Telescope. Credit: Allen Foster

ALLEN FOSTER:

Greasing Telescope Gears During a 7-Month-Long Night

While overwintering in Antarctica, Foster maintains the South Pole Telescope facilities.

While people were isolating in their homes at the start of the COVID-19 pandemic, Allen Foster was in the "only place on Earth that didn't have COVID": the Amundsen-Scott South Pole Station in Antarctica. He was there working on the South Pole Telescope (SPT). "It was kind of a surreal thing," said Foster, a Ph.D. candidate at Case Western Reserve University in Cleveland.

During his 10-month South Pole assignment in 2019, Foster focused on determining how well the SPT could sort light from some of the most extreme phenomena in the universe: the cosmic microwave background and black holes.

Foster has the unique and rare experience of being one of only around a thousand people each year who overwinter in Antarctica. Not only do temperatures fall to nearly −80°C (−110°F), but also darkness covers the land throughout the entire 7-month season (February through August), making many scientists steer clear of such a tough work environment.

Although some polar scientists can suffer from winter-over syndrome, "I love being in Antarctica," said Foster. During the long, dark winter, he enjoys seeing "all the dust splotches in the galaxy and the superbright, super colorful auroras." He has gotten used to the continent's extreme temperatures and regularly records his thoughts and experiences in his blog.

In 2022, Foster found himself back at the South Pole as a telescope operator, about a year after his first stint at the station. He now is responsible for scheduling observations using the SPT as well as installing and maintaining the equipment, which includes "lots of greasing." He also helps train new SPT crew.

The SPT keeps Foster busy. The telescope is part of the global Event Horizon Telescope array, which aims to image objects the size of a supermassive black hole's event horizon. In March 2022, the Event Horizon Telescope's 2-week observation window to search for black holes, galaxies, and quasars meant 16-hour workdays for Foster. These stretches weren't actually work *days*, he said. "[They] happened to be overnight for us because we're in a weird time zone."

Foster is also working on his doctoral thesis using observations and data from the SPT to look for deep solar system objects like the possible Planet 9. If this planet exists, it would be so far from the Sun that it would be very difficult to observe through an optical telescope. But according to Foster, "it's possible it has a reasonably strong thermal emission, which would be visible to the SPT-3G experiment" (the third survey receiver operating on the South Pole Telescope dedicated to high-resolution observations of the cosmic microwave background). He hopes his thesis will show the power and possibilities of the SPT for future observations of distant celestial objects at millimeter wavelengths.

—Santiago Flórez (@rflorezsantiago), Science Writer

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Microbes Might Munch Magnetic Minerals at Oil Spill Site

A new pipeline is installed in 2009 through the Bemidji oil spill site in Minnesota. Credit: Andrew Berg

In August 1979, an oil pipeline burst near Bemidji, Minn., spraying 1.7 million liters of crude oil onto the ground. Following cleanup, 400,000 liters that had seeped into sediments still remained. Recognizing a unique opportunity, research groups began to study the site to gain new insights into the long-term dynamics of oil spills.

Since then, some studies have observed changes in the magnetic properties of contaminated sediments at what is now known as the National Crude Oil Spill Fate and Natural Attenuation Research Site, managed by the U.S. Geological Survey. Such magnetic changes can reflect—and therefore help monitor—the degradation of spilled oil.

In 2014, scientists first reported a strong magnetic response within the oil layer. However, by the end of 2015, the magnetization had almost totally disappeared. Now, *Ohenhen et al.* report new observations that illuminate the processes likely responsible for the changes in magnetism at the Bemidji site. Specifically, a magnetic, iron-containing mineral known as magnetite in the sediment appears to be both dissolving and undergoing conversion into the less magnetic mineral maghemite, and microbes may be driving much of this conversion.

Between 2016 and 2019, sediment cores were sampled from various parts of the spill site, and the researchers measured their magnetic and mineral properties at the Institute for Rock Magnetism. The scientists also installed packets of magnetite below the water table in the spill site and sampled them periodically to capture any changes.

In line with earlier data, the experiments showed that magnetization in the sediments decreased over time. However, the data point to a few potential processes underlying the decreased magnetization, which may vary depending on the precise location in the spill site.

In sediments outside of the remaining underground oil plume, the data suggest that a minor decrease in magnetization occurred via conversion of magnetite to maghemite through a nonbiological chemical process that relies on oxygen. Within the plume, the researchers found evidence, including signs of decreased sediment grain size, for a combination of dissolving magnetite and conversion to maghemite.

It is of note that conversion to maghemite within the plume occurs in a zone known to contain very little oxygen. Yet nonbiological conversion is typically driven by oxygen. Thus, the researchers hypothesize, within-plume conversion may occur as a result of life-sustaining biological processes of anaerobic microbes in this zone.

These findings add to a body of evidence suggesting that microbes can alter the magnetism of Earth materials. Future research could help identify specific microbes that may convert magnetite to maghemite at the Bemidji site. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006560, 2022) **—Sarah Stanley,** *Science Writer*

Simulating 195 Million Years of Global Climate in the Mesozoic

The Mesozoic, which stretched from about 252 million to 66 million years ago, was a pivotal period in Earth's history. In addition to being the age of the dinosaurs, it was when the supercontinent Pangaea began to separate into the fragmented continents we're familiar with today. Together with elevated levels of carbon dioxide and the brightening Sun, tectonic changes influenced global climate, producing warm and humid greenhouse conditions. A detailed understanding of the factors that drove Mesozoic climate trends will not only provide insight into Earth's history but also help scientists study the consequences of human-caused warming of our planet.

One approach to investigating past climates is using numerical models. In a new study, *Landwehrs et al.* performed an ensemble of climate simulations covering a period from 255 million to 60 million years ago in 5-million-year time steps. They adjusted specific parameters in different runs to dissect the sensitivity of past climates to paleogeography, atmospheric carbon dioxide levels, sea level, vegetation patterns, the Sun's energy output, and variations in Earth's orbit.

The authors found that global mean temperatures during the Mesozoic were generally higher than preindustrial values. They also observed a warming trend, driven by increasing solar luminosity and rising sea levels. Ocean areas typically reflect less solar radiation than land; accordingly, the researchers found that higher sea levels and flooding of continental areas coincided with warmer global mean temperatures. Concurrent with this general trend, fluctuations in atmospheric carbon dioxide produced warm and cool anomalies in global mean temperature. The authors note that this finding does not mean that human-induced global warming should be ignored; modern climate is changing much faster than it did in Earth's history.

The ensemble of climate simulations provides insight into other aspects of long-term Mesozoic climate change as well. Overall, the authors identified a transition from a strongly seasonal and arid Pangaean climate to a more balanced and humid climate. To aid additional analyses of Mesozoic climate trends, the authors shared their model data online. (*Paleoceanography and Paleoclimatology*, http://doi.org/10.1029/2020PA004134, 2021) **—Jack Lee,** *Science Writer*

Quantifying the Health Benefits of a U.S. Clean Energy Transition

Energy-related emissions in the electric power, transportation, building, and industry sectors take a direct toll on human health in the form of air pollution. Fine particulate matter ($PM_{2.5}$) is one of the biggest health risks to communities living in highly polluted areas. Chronic exposure to $PM_{2.5}$ can lead to a wide range of health problems, including respiratory infections, cancer, heart disease, stroke, and possibly dementia. These health problems often disproportionately affect the most vulnerable communities.

Since 2015, states across the United States have begun to set ambitious emissions reduction plans. For example, Massachusetts passed legislation to put the state on track to reach net zero greenhouse gas emissions. However, the country still isn't decarbonizing at a rate fast enough to meet Paris Agreement targets and avoid the worst outcomes of global warming. Quantifying the health effects of energy-related emissions—and the benefits of a transition to renewable energy sources—could support a public health–focused rationale for transitioning to clean energy sources.

In a new study, *Mailloux et al.* estimate the health benefits of completely removing $PM_{2.5}$ and related emissions from the U.S. energy system. They used EPA's CO-Benefits Risk Assessment screening tool, which allows policymakers and researchers to estimate the health impacts of various emissions scenarios.

They found that removing all of the United States' energy-related sources of $PM_{2.5}$, along with the associated pollutants sulfur dioxide and nitrogen oxides, could prevent roughly 50,000 premature deaths per year. In addition, they found that a transition away from burning fossil fuels could save an estimated $608 billion in the health care costs and loss of life associated with $PM_{2.5}$. Of all the sectors, removal of emissions from on-road vehicles made the single biggest difference in terms of avoided premature deaths and monetized health benefits.

These findings could strengthen the case for a national clean energy policy in the United States, according to the authors. Their analysis showed that as many as 33 states would receive at least twice the benefit from nationwide action compared with state-specific policies. The authors stress, however, that regional clean energy policies remain valuable and could still save thousands of lives each year. (*GeoHealth*, https://doi.org/10.1029/2022GH000603, 2022) **—Rachel Fritts,** *Science Writer*

Fine particulate matter ($PM_{2.5}$), a pollutant emitted when fossil fuels are burned, is associated with an increased risk of heart disease, cancer, stroke, and other life-threatening illnesses. Credit: Robert S. Donovan/Earthjustice, CC BY-NC 2.0 (bit.ly/ccbync2-0)

Estimating Heat Wave Frequency and Strength: A Chicago Case Study

Urbanization and human-caused climate changes have led to increases in heat events around the world. For example, in July 2012, an extreme heat wave hit the Chicago areas, causing temperatures to skyrocket to 40°C (104°F) and above. Chicago, like most cities, is affected by urban heat islands (UHIs), which occur when changes in land cover create spaces that are warmer than their surrounding area. Satellite measurements can be used to inform models to characterize the intensity of UHIs, yet satellite techniques have some limitations—expensive sensors and low temporal resolution, among other drawbacks. But quantifying the intensity of UHIs could help public health officials and city planners learn to mitigate the impacts of future heat waves.

In a new study, *Chen et al.* use numerical modeling and real-world measurements to assess the impacts of the Chicago heat wave on the city and the surrounding region. The researchers used the National Center for Atmospheric Research's Weather Research and Forecasting (WRF) model—a framework that's commonly used for both atmospheric research and weather forecasting—together with the High-Resolution Land Data Assimilation System, which adds information about soil moisture to the WRF.

The authors found that application of the Multi-Layer Urban Canopy Model (MLUCM) in WRF provided the best estimates of the heat wave's effects on Chicago and the surrounding areas. Using data and measurements taken during the 2012 heat wave, the researchers found that daytime temperatures in urban areas were around 3°C higher than usual during the heat wave, whereas rural temperatures were about 4°C higher. They estimated that urban heat island effects led city temperatures to be 1.44°C–2.83°C higher than they otherwise would have been. In urban areas, the excessive heat factor (a statistical index to represent heat stress) reached 50°C^2—a level likely to cause health problems.

Urban and rural areas both experienced advantages and disadvantages during the heat wave. The city got a bit of a reprieve because of the breeze from Lake Michigan—a benefit not experienced in rural areas—but the city's nighttime temperature still remained dangerously high. Rural areas, on the other hand, benefited from the heat-mitigating effects of vegetation. People in rural areas are typically less adapted to high temperatures and lack the medical resources of city residents, leaving rural residents potentially less able than city residents to cope with a heat wave's health impacts.

Incorporating benefits of rural areas, such as vegetation and permeable surfaces, into urban centers will help keep these areas livable during hot summers, the authors suggest. Conversely, providing supplemental medical support to rural areas could help residents ride out future heat waves. (*GeoHealth*, https://doi.org/10.1029/2021GH000535, 2022) **—Saima May Sidik,** *Science Writer*

Solar Wind a Major Driver of Atmospheric Sodium at Mercury

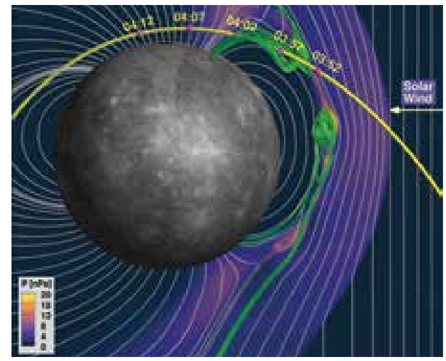
No object in the solar system experiences the solar wind more powerfully than Mercury. The planet's magnetic field deflects the Sun's stream of electrically charged particles at a distance of only 1,000 kilometers from Mercury's surface, a point called the magnetopause.

The Sun's magnetic field lines are carried by the solar wind and bend as they collide with those of Mercury. When conditions are right, these bent lines break and meet with those of Mercury in an event called magnetic reconnection. During reconnection, particles from the solar wind can penetrate Mercury's magnetic field. These particle transmissions are called flux transfer events (FTEs), and a burst of FTEs in rapid succession is known as an FTE shower.

Sun et al. investigated the effect of these showers on the planet's surface using data collected by NASA's MESSENGER (Mercury Surface, Space Environment, Geochemistry, and Ranging) spacecraft, which orbited Mercury between 2011 and 2015. As the spacecraft passed through Mercury's magnetopause and toward the surface, the onboard ion mass spectrometer, FIPS (Fast Imaging Plasma Spectrometer), recorded the local abundances of sodium group ions, including sodium, magnesium, aluminum, and silicon ions. Simultaneously, an onboard magnetometer measured the local magnetic environment. During the course of MESSENGER's orbital mission, this scenario occurred 3,748 times, and half included the observation of an FTE shower.

The authors performed a statistical analysis of the abundance of sodium group ions in Mercury's atmosphere. During approaches coincident with an FTE shower, they found that the abundance of sodium group ions in the atmosphere is about 50% higher than during non-FTE shower periods. After examining several potential mechanisms for this enhancement, the scientists concluded that sputtering from the solar wind is the most likely cause.

These MESSENGER observations are an important indicator of the dynamism of Mercury's thin atmosphere, according to the authors. More information is likely to come in early 2026 when the joint European-Japanese mission BepiColombo arrives at Mercury. The mission consists of two spacecraft, one targeted at Mercury and one targeted at its magnetosphere. Working in concert, they should provide unprecedented detail on FTE-induced solar wind sputtering. (*Journal of Geophysical Research: Space Physics,* https://doi.org/10.1029/2022JA030280, 2022) **—Morgan Rehnberg,** *Science Writer*



This still from a computer simulation shows solar wind entry layer and flux transfer events (green lines) in Mercury's dayside magnetosphere. Credit: Sun et al.

Assessing Water Infrastructure Investments in California

With water scarcity increasing around the globe, arid regions are striving to develop more flexible and diversified water supplies. For example, California's 2020 Water Resilience Portfolio Initiative recommends improving and expanding the state's conveyance and storage infrastructure as well as developing groundwater banking and other means of more flexibly sharing water. The success of such initiatives depends in large part on the ability of water providers to collaboratively finance and build new infrastructure.

To date, most water supply and storage planning has relied on models that analyze average, project-level outcomes. But new research by *Hamilton et al.* in California's southern Central Valley suggests that these tools no longer suffice, especially when planning under future climate uncertainty.

The team used the water resources simulation model CALFEWS (California Food-Energy-Water System) to evaluate thousands of potential partnership structures for each of three capital projects—rehabilitation of the Friant-Kern Canal, development of a hypothetical groundwater bank, or both—under wet, average, and dry 50-year hydrologic scenarios. The results indicate that even without considering future climate change, most water infrastructure partnerships resulted in unequal costs, risks, and benefits across individual water providers.

Of the more than 27,000 scenarios the authors evaluated, only 8% were able to distribute new water to each partner for less than $200 per million liters ($247 per acre-foot), a cost significantly higher than the of $32–$154 per million liters ($40–$190 per acre-foot) typically charged by water districts in the region today. Just 1% of the scenarios were viable under dry hydrologic conditions or when canal expansion was the only capital project considered.

These findings indicate that climate-related risk is often unevenly distributed between water providers. What's more, the financial viability of water infrastructure projects is strongly shaped by the partnership design, including which providers participate and how the debt is distributed among them.

Given the increasing frequency and severity of droughts, new methods for designing viable water infrastructure projects are more important than ever. Insights from this research could help decisionmakers chart a new, more sustainable path for enhancing water resilience in California and in other arid regions around the globe, according to the authors. (*Earth's Future,* https://doi.org/10.1029/2021EF002573, 2022) **—Terri Cook,** *Science Writer*

Half of U.S. Tidal Marsh Areas Vulnerable to Rising Seas

Tidal marshes like this one in Washington State's Mary E. Theler Wetlands Nature Preserve may be threatened by rising seas. New research highlights the variable vulnerability of U.S. tidal marshes to rising seas. Credit: Joe Mabel, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Sea level is rising worldwide, thanks in large part to climate change. Rising seas threaten coastal communities and ecosystems, including marshes that lie at the interface between salt water and fresh water. Tidal marsh ecosystems feature distinct plants and play key ecological roles, such as serving as nurseries for fish. It is known that some tidal marshes can avoid destruction by migrating inland or through formation of new soil that raises their elevation, but a better understanding of how they are affected by rising seas could inform efforts to plan for and mitigate the effects.

New research by *Holmquist et al.* investigates the vulnerability of tidal marshes to sea level rise across the contiguous United States. The findings show, for the first time, that opportunities for resilience differ between more northerly and more southerly marshes across the country.

To help clarify the fate of tidal marshes in the United States, the researchers combined tide gauge data on sea level rise rates with soil formation rates reported in previous studies. They also incorporated information from local maps of water level, elevation, and land cover. Using these data, they calculated the potential for the marshes to adapt to rising seas by 2100 under several climate change scenarios.

The analysis revealed that different tidal marshes have different pathways for resilience to sea level rise. Specifically, more northerly marshes are more likely to lack opportunities to migrate inland, whereas more southerly marshes are more likely to lack the capacity to form and build up enough soil to keep pace with sea level rise.

The researchers also found that depending on the degree of climate change, 43%–48% of tidal marsh area in the United States is vulnerable to destruction by sea level rise. These vulnerable areas tend to occur along the Gulf of Mexico and mid-Atlantic coasts, at sites where opportunities for both inland migration and vertical soil buildup are limited.

This study highlights the importance of considering local conditions when gauging the vulnerability of tidal marshes to rising seas. The findings could aid future research and planning efforts. (*Earth's Future*, https://doi.org/10.1029/2020EF001804, 2021) **—Sarah Stanley,** *Science Writer*

Modeling Atmospheric Waves from Hunga Tonga–Hunga Ha'apai

On 15 January 2022, the Hunga Tonga–Hunga Ha'apai volcano erupted underwater between two uninhabited islands in the South Pacific's Kingdom of Tonga. The once-in-a-thousand-year blast, whose plume reached 30 kilometers (nearly 19 miles) high, also rippled atmospheric waves around the globe. Sensors detected inertia gravity waves, infrasound waves, and Rossby waves near the eruption site. Farther afield, NASA satellites picked up Lamb waves repeatedly circling Earth.

In a new study, *Amores et al.* simulated the air pressure waves propagated by the eruption in an effort to confirm that the Hunga Tonga–Hunga Ha'apai eruption generated the Lamb waves that bounced around the planet. They used a shallow-water oceanic model to simulate the atmospheric waves.

The results showed excellent agreement with satellite and in situ observations of Lamb waves that moved around the globe. The authors note that when compared to atmospheric pressure records, the model outputs were remarkably accurate in matching the arrival time of the pressure waves at different sensors. The results confirmed that the surface oscillations following the eruption did originate from the volcano.

Despite the limitations imposed by using an ocean model toimulate atmospheric waves, the approach aptly captured the main physical mechanisms of the Lamb waves, according to the authors. The methods revealed how an ocean model could show the propagation of Lamb waves through the atmosphere following future volcanic perturbations. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL098240, 2022) **—Aaron Sidder,** *Science Writer*

Faulting and Folding Signals in Seismic Data

Earth's crust is constantly in motion. As tectonic plates that make up the lithosphere shift, pulling apart and crashing into each other, the crust fractures and folds in response. Both faulting and folding play out at fault-bend folds, which are created by ramp-décollement systems, but the dynamics and timing of folding in relation to earthquake cycles are not well understood.

In search of answers, *Mallick et al.* developed a numerical model to simulate folding in the brittle crust throughout the earthquake cycle, which accounts for the mechanical relationship between fault slip and inelastic off-fault deformation. The team derived the shear stressing rate from incremental deformation using elastoplastic models of folding and combined it with earthquake sequence simulations and rate-state frictional models of fault strength evolution.

The authors found that the elastic response of the crust to fault slip can obscure the inelastic deformation in geodetic data during large earthquakes but that it's possible to distinguish between these signals in the postseismic period. They show that the rate of off-fault deformation is tightly linked to fault slip, with the greatest rates occurring during and immediately following earthquakes and tapering off logarithmically over time. What's more, they found that the type of rock present can influence this rate of relaxation.

To tease out the geodetic signals of off-fault deformation from those of on-fault release, the authors recommend that future studies combine seismogeodetic observations with structural geological data on fault geometry. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB022045, 2021) **—Kate Wheeling**, *Science Writer*

Dynamics of Ocean Worlds Likely Controlled by Their Rotation

NASA's Cassini spacecraft captured Europa with Jupiter. Credit: NASA/JPL/SSI

Discovering that many of the large moons in the outer solar system may host significant subsurface oceansof liquid water has been a key advance in planetary science. These moons represent some of the most promising habitats for life beyond Earth, but their hidden nature makes direct study difficult.

These oceans appear to be tens or even hundreds of kilometers deep, bounded at the top by a thick, icy shell and at the bottom by a source of geothermal heating. A key element to understanding their nature is to deduce the patterns of ocean circulation, because it is the ocean that transports heat, salt, and potential biosignatures to the surface, where they could be detected by future space missions.

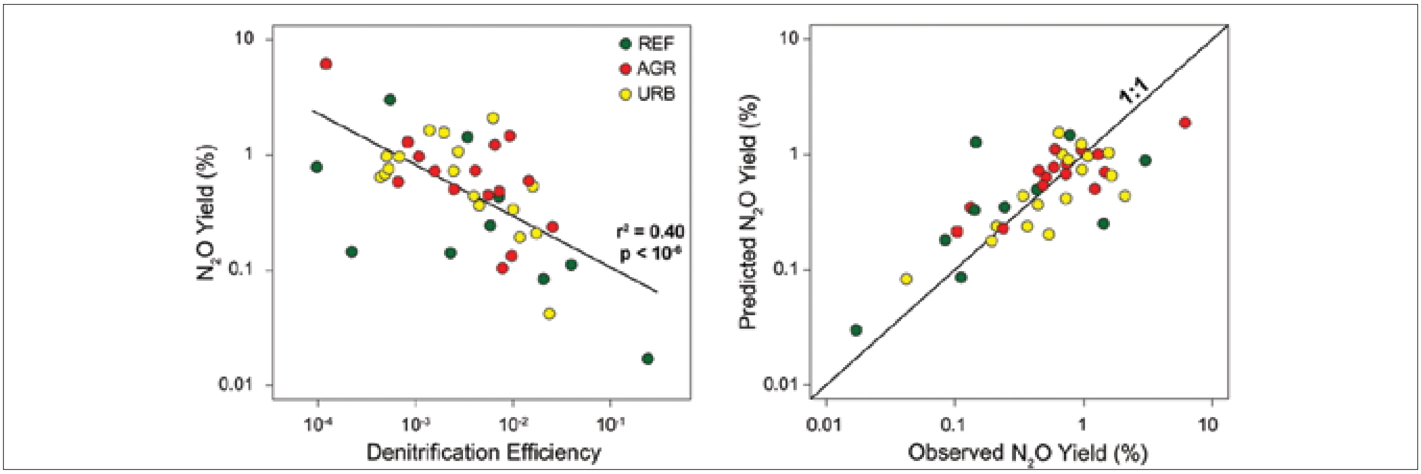
Although some previous studies have simulated the dynamics of subsurface oceans, those calculations have relied on parameters that are poorly constrained by observations. In a new study, *Bire et al.* pursued a novel approach by casting their simulations in terms of a dimensionless number—the natural Rossby number, which is a ratio of buoyancy flux, moon rotation rate, and ocean depth—for which observational constraints do exist.

The authors present a series of simultions that explore a wide parameter range of ocean depth, moon rotation rate, and driving heat flux. In the small-Rossby number regime likely appropriate for icy moons, the simulated moon's rate of rotation has a strong effect on the dynamics of the subsurface ocean. This stands in contrast to the currently accepted model.

Consistent with arguments rooted in well-understood rotating fluid dynamics in a spherical shell, the ocean's circulation breaks into two regions. At higher latitudes, convective plumes extend upward parallel to the moon's axis of rotation from the bottom to the top. But at lower latitudes, water is carried around the moon longitudinally and interacts less strongly with the ocean floor. This flow pattern likely dampens how efficiently geothermal heat from deep within the moon can be transferred across the ocean up to the surface. Therefore, equatorial regions are less efficient than polar regions at heat transport, with important implications for the thickness of the ice shell at the surface.

According to the authors, turbulence created by the global convective process likely led to the creation of bands of alternating ocean currents, similar to the mechanism that generates the colorful zones and belts found in Jupiter's atmosphere. In fact, the general circulation pattern found within the oceans of these outer solar system moons may bear remarkable similarity to that of Jupiter. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2021JE007025, 2022) **—Morgan Rehnberg**, *Science Writer*

What Controls Nitrous Oxide Emissions from Rivers?



Statistical modeling of nitrous oxide (N_2O) yields from streams—the fraction of nitrogen in the water that ends up being released to the atmosphere as N_2O—shows that denitrification efficiency (the proportion of nitrate that is chemically reduced via denitrification at the streambed) is the most important determinant of these yields. Credit: Winnick, 2021

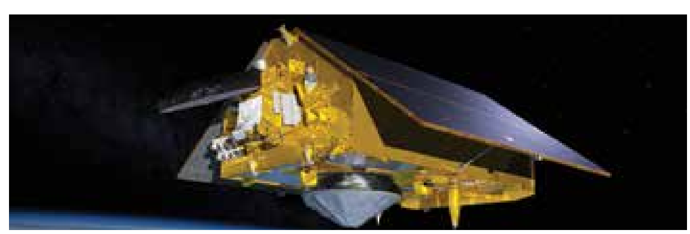
River systems are important sources of the powerful greenhouse gas nitrous oxide (N_2O). Their emissions have grown substantially in recent decades, largely due to the increasing amount of nitrogen-bearing fertilizer that ends up in rivers. *Winnick* shows, through analysis of an extensive experimental data set as well as by numerical modeling, that denitrification (the conversion of fixed nitrogen into harmless nitrogen (N_2) gas) in river systems can alleviate part of this problem. He finds that river systems in which denitrification is very active, thanks to the presence of microzones devoid of oxygen, have low N_2O yields.

This finding implies that river restoration projects in regions with high nitrogen loads should aim to create many such anoxic microzones in the streambed, for example, by reducing flow speed. Doing so would not only reduce the fixed nitrogen loads in the river but also reduce the amount of N_2O released to the atmosphere. (https://doi.org/10.1029/2021AV000517, 2021) **—Nicolas Gruber**

Transforming Hydrology by Integrating Sensors and Disciplines

Spaceborne remote sensing technologies and approaches have advanced to a stage in which observations of global processes are possible. These observations will lead to new insights and discoveries that improve our understanding of how hydrologic processes are globally interlinked, illuminating the role of the hydrologic cycle in weather, climate, and the biosphere. But we must consider whether the improved observations and advanced understanding will be sufficient to address emerging problems related to water and the environment in a global sense.

Durand et al. summarize progress in estimating the terms of water balance, storage, and fluxes, predominantly from spaceborne sensors. Their review leads to a recommendation to optimize the benefits of remote sensing to advance research and address emerging problems by integrating multidisciplinary approaches with data from multiple sensors; leveraging commercial satellite measurements; and using data assimilation, cloud computing, and machine learning. (https://doi.org/10.1029/2021AV000455, 2021) **—Tissa Illangasekare**



The Sentinel-6 Michael Freilich satellite, which remotely monitors hydrologic processes, orbits Earth in this artist's depiction. Credit: NASA

PRINCETON UNIVERSITY

PROJECTING CHANGING HYDROCLIMATE EXTREMES OVER WESTERN U.S. ON DECADAL TO MULTIDECADAL TIME SCALES

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks one or more postdoctoral or more senior researcher for research related to predicting and projecting changes in Western United States hydroclimate and extremes on decadal to multidecadal time scales, including observed and simulated changes in river flows. The research will make extensive use of both observations and a variety of modeling tools, including the latest generation of GFDL climate models. The selected candidate will analyze large data sets from observations and from multiple large ensembles conducted with high-resolution versions of the GFDL SPEAR model, with atmosphere-land horizontal resolutions as fine as 25 km. These ensembles span the period 1921-2100 and will be used to explore projected changes in hydroclimate extremes over the Western United States, especially on regional scales. The incumbent may also use real-time seasonal to decadal predictions and hindcasts with SPEAR to explore predictions of extremes on seasonal to decadal scales. The incumbent will be encouraged to use novel diagnostic techniques and new physical insights to explore these topics.

The selected candidate will have one or more of the following attributes: (a) a strong background in climate dynamics or a closely related field, (b) experience using and analyzing climate models, and (c) strong diagnostic skills in analyzing large data sets.

Candidates must have a Ph.D. in Atmospheric Science, Oceanography, or a closely related field. The initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding.

Princeton is interested in candidates who, through their research, will contribute to the diversity and excellence of the academic community. Applicants should apply online to at **https://www.princeton.edu/acad-positions/position/26347**. Complete applications including a CV, publication list, 3 letters of recommendation and a one-to-two page research statement. Review of applications will begin **September 20, 2022**, and continue until the position is filled. For additional information, contact Tom Delworth (**tom.delworth@noaa.gov**).

This position is subject to the University's background check policy.

Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Greetings from the sea ice just offshore of Utqiagvik, Alaska!

As part of an Arctic geophysics research class, Radford University students (left to right) Nick Terehoff, Jonathon Halferty, Matthew White, and Grace Psenicska deploy sensors of their own design to measure properties of the ice and its surroundings. Some students are measuring wind velocities at multiple heights to study the boundary layer at different locations on the ice. Others are deploying shaded temperature sensors to investigate heat transfer from the warmer ice surface to the colder air layers above. In each course offering, students come up with their own research ideas and make their own microcontroller-based sensors from scratch.

—**Rhett Herman,** Radford University, Radford, Va.

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