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SCIENCE NEWS BY AGU
VOL. 105 | NO. 9
SEPTEMBER 2024

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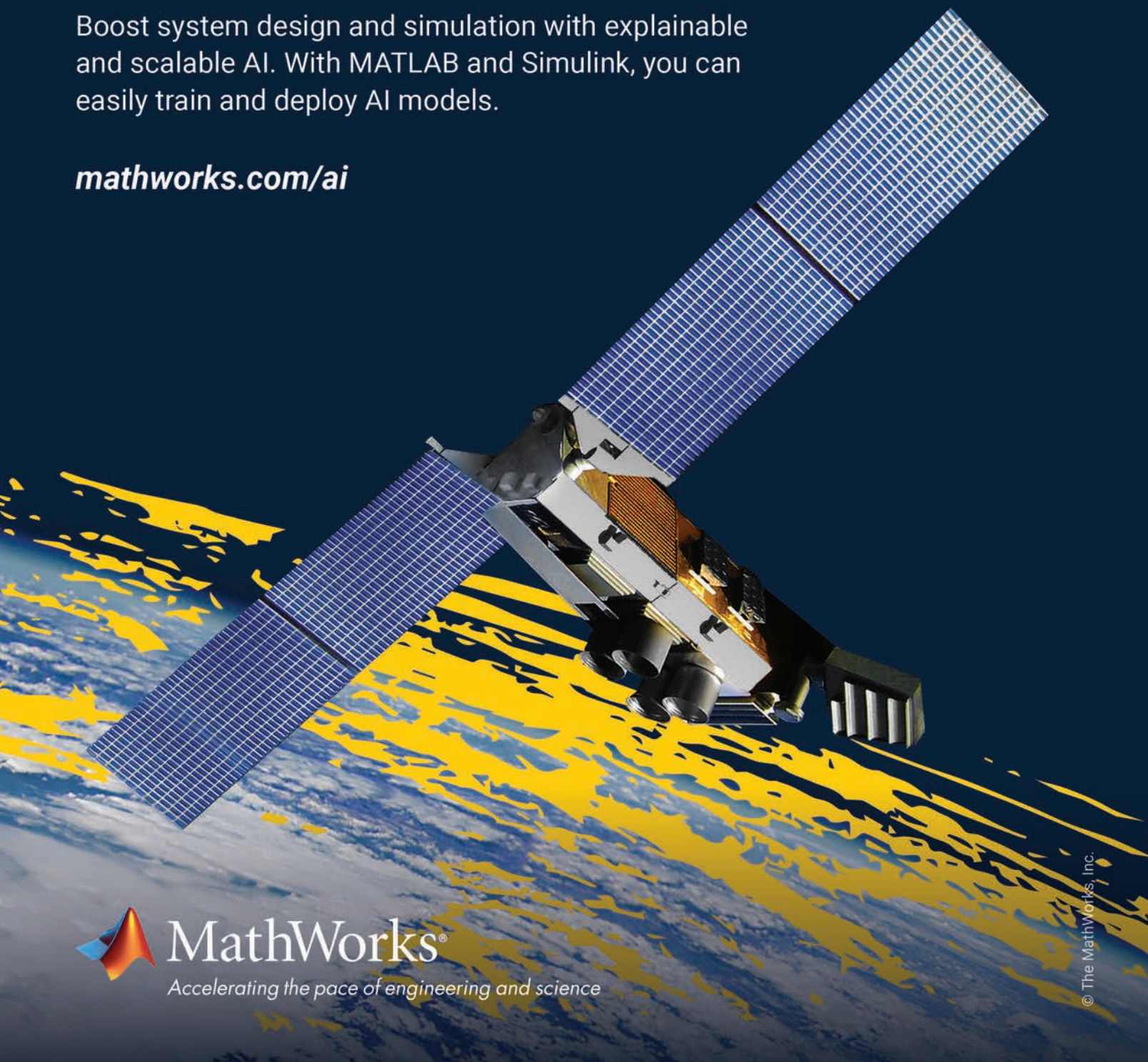

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From the Editor

Geoscience departments and programs on campuses across the United States (and elsewhere) face many challenges to their survival. Not least of these are perceptions that they are nonessential and that their courses and cultures do not match students' interests. Countering these perceptions often requires difficult but necessary measures to rebrand or reshape. In "Geoscience Departments Can 'Phone a Friend' for Support," (p. 22) learn from two insiders about the Traveling Workshops Program, which for a decade has been guiding departments through needed conversations and helping them adapt to their changing environments.

On the Cover

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Eos: Science News by AGU (ISSN 0096-3941) is published monthly except December by the American Geophysical Union, 2000 Florida Ave., NW, Washington, DC 20009, USA. Periodical Class postage paid at Washington, D.C., and at additional mailing offices. POSTMASTER: Send address changes to *Eos: Science News by AGU*, Member Service Center, 2000 Florida Ave., NW, Washington, DC 20009, USA

Member Service Center: 8:00 a.m.–6:00 p.m. Eastern time; Tel: +1-202-462-6900; Fax: +1-202-328-0566; Tel. orders in U.S.: 1-800-966-2481; service@agu.org.

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Janice Lachance, Interim Executive Director/CEO

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Creativity Prize

[1] The team of Maria Cristina Rulli (Polytechnic of Milan, Italy) and Paolo D'Odorico (University of California, Berkeley, USA)

for spearheading novel analyses of the water-energy-food nexus that describe how numerous complex factors interact, providing for better freshwater stewardship in a changing, globalised world.

Maria Cristina Rulli

Paolo D'Odorico

[2] The team of Zhiguo He (Zhejiang University, China)

for developing working, versatile soft robots with unprecedented manoeuvrability that have the capacity for numerous underwater research and monitoring applications. Team members include: Pengcheng Jiao and Yang Yang.

Zhiguo He

Surface Water Prize

Qiuhua Liang (Loughborough University, UK) and his team

for developing innovative, open-source, multi-GPU hydrodynamic models to support real-time flood forecasting at fine temporal resolutions. Team members include: Huili Chen, Xiaodong Ming, Xilin Xia, Yan Xiong and Jiaheng Zhao.

Qiuhua Liang

Groundwater Prize

Chunmiao Zheng (EIT, Ningbo, China) and his team

for powerful management tools to understand groundwater processes in ecohydrologic systems under diverse hydrological and climatic conditions, considering environmental and socioeconomic factors at local and national scales.

Chunmiao Zheng

Alternative Water Resources Prize

Virender K. Sharma (Texas A&M University, USA) and his team

for the effective removal of antibiotics and pharmaceuticals from wastewater through advanced oxidative processes by activated ferrate, which work at high, even enhanced, efficiency in water containing commonly occurring natural organic matter. Team members include: Ching-Hua Huang, Chetan Jinadatha and Radek Zbořil.

Virender K. Sharma

Water Management & Protection Prize

Joseph Hun-wei Lee (Macau University of Science & Technology, China)

for developing unique and highly effective hydro-environmental modelling systems for the sustainable water management of smart cities.

Joseph Hun-wei Lee

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Potential Relief for the Colorado River's Near Future

Drought has plagued the Colorado River for the past 2 decades, but a recent study showed that the river's flow could bounce back over the next 25 years due to increased precipitation.

The Colorado River stretches more than 2,400 kilometers from its Rocky Mountain headwaters in Wyoming and Colorado to the Gulf of California in Mexico and supplies water to residents, industry, and agriculture in seven U.S. states.

"Nature has inherent variability in its precipitation patterns—at times these deliver abundant moisture; at other times, the opposite."

In the U.S. Southwest, however, the 2000–2021 period was the driest in the past 1,200 years. The multidecadal drought has driven flows of the Colorado River to historic lows. Increasing temperatures due to climate change have led to concerns that these flows will continue to decline.

"The narrative that we read a lot about is that there's no chance of recovery from our recent woes, as temperatures will keep warming and deplete more water," said climate scientist Martin P. Hoerling of the University of Colorado Boulder, a coauthor of the study. "And we need to therefore confront a very dire outlook for the future."

Hoerling's previous research, however, indicated that precipitation, not temperature, has been the predominant factor affecting the flows of the Colorado River (bit.ly/CO-river-decline). A couple decades of extremely low precipitation have been the main cause of the recent decline, Hoerling said. "Nature has inherent variability in its precipitation patterns—at times these deliver abundant moisture; at other times, the opposite," he said.

Stakeholders are beginning deliberations on post-2026 guidelines for managing future Colorado River water resources. And researchers have been working to parse the effects of both temperature and precipitation—their cyclical variations and trends—on this vital resource. "This includes understanding how much of our current drought is due to human influences versus natural swings," Hoerling said. "Because that's what is going to best inform if, and how, the river's flow will recover."

The Colorado River cuts a path through silt and mud near Hite Marina, Utah. Credit: Alexander Heilner/The Water Desk, with aerial support provided by LightHawk; CC BY-NC-ND 4.0 (bit.ly/ccbyncnd4-0)

Good News and Bad News

To start answering these questions, the researchers compared precipitation and temperature data to water flow records at Lee Ferry in Arizona—the dividing point of the river's Upper and Lower Basins—which date back to 1895. Lee Ferry is the historical gauge, and almost all of the water in the river originates above this point.

Their analysis found that 80% of the recent low flows, compared with the average flow measured at the beginning of the 20th century, was due to low precipitation and 20% was due to rising temperatures. "So, again, it's consistent with our view that historically, precipitation is driving the bus," Hoerling said.

The researchers then used a collection of high-resolution climate models to simulate the river's flow through 2050, should temperatures continue to rise. They assumed three different flow sensitivities to temperature increases.

"We are adding a bit of light to the story by presenting a more complete picture of recovery odds."

The projections indicated a 70% chance of increased precipitation in the Upper Basin during 2026–2050. The magnitude of increases, relative to recent decades, could compensate for the negative effects of further warming, leading to a net increase in river flows, Hoerling said.

"The standing narrative is a dark one based on temperature projections alone, and we are adding a bit of light to the story by presenting a more complete picture of recovery odds," he said.

The study's findings also highlight the need for caution, however: The projections suggested a 4% chance that the annual flow

of the river averaged for 2026–2050 could be as low as 10 million acre-feet—a 20% reduction from the current level. "If that were to come to pass, it would be unfortunate," Hoerling said. "But if you were unprepared, it could be disastrous."

"The study is a good reminder to water managers and policymakers that there's a wide range of possibilities for what is going to happen to Colorado River flow in the next 2 decades."

Forewarned Is Forearmed

The teams findings were published in the *Journal of Climate* (bit.ly/CO-river-future). The study indicates that the future of the river is not entirely bleak but that both high and low flows are more likely in future decades.

"The message for the water community is that the drier 'dries' and the wetter 'wets' are all connected," said coauthor Eric Kuhn, the retired general manager of the Colorado River Water Conservation District.

"The study is a good reminder to water managers and policymakers that there's a wide range of possibilities for what is going to happen to Colorado River flow in the next 2 decades," said hydroclimatologist Park Williams of the University of California, Los Angeles, who was not involved with the study. "And the way that we choose to manage the river and allocate the river needs to be able to accommodate all of those possible future scenarios."

The study presumes, however, that the effect of temperature on river flow and streamflow is relatively weak, which is an assumption that requires further investigation, Williams said. "How the Colorado River will be affected by global warming is so important that we need to continue beyond the analysis provided in this paper," he said.

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

As the Caspian Sea Recedes, Tectonics May Help Shape Its Coastline

This view of the Caspian Sea was captured over Azerbaijan by members of International Space Station Expedition 56 in June 2018. Credit: NASA Johnson Space Center/Wikimedia Commons

Earth's largest inland body of water, the Caspian Sea, has been rapidly shrinking for the past 30 years because of a warmer, drier climate and increasing water use upstream. The sea's retreat—it's level is expected to drop by up to 18 meters (60 feet) from its 2020 level by 2100—is threatening ecosystems, hindering port activity, and spurring local authorities to declare states of emergency.

The speed and shape of changes to the Caspian Sea's coastline depend on a variety of geologic and anthropogenic forces, according to new research presented at the European Geosciences Union General Assembly 2024 in Vienna. Scientists said their findings will help land managers better prepare human and ecological communities for sea level changes.

"It's important to know what the local geologic effects are to be able to better plan for these wetlands in the future," said Eric Fielding, a geophysicist at NASA's Jet Propulsion Laboratory and a coauthor of the new study.

A Shrinking Sea and Uplifting News

Researchers analyzed data from the European Space Agency's Sentinel-1 mission, which measured the vertical motion of land between 2014 and 2023.

They focused their analysis on changes to the Gizil-Aghaj State Reserve, a wetland that borders the Caspian Sea in southeastern Azerbaijan. Satellite imagery shows that since 2014, the Gizil-Aghaj coastline has shifted to expose an additional 218 square kilometers (84 square miles) of land.

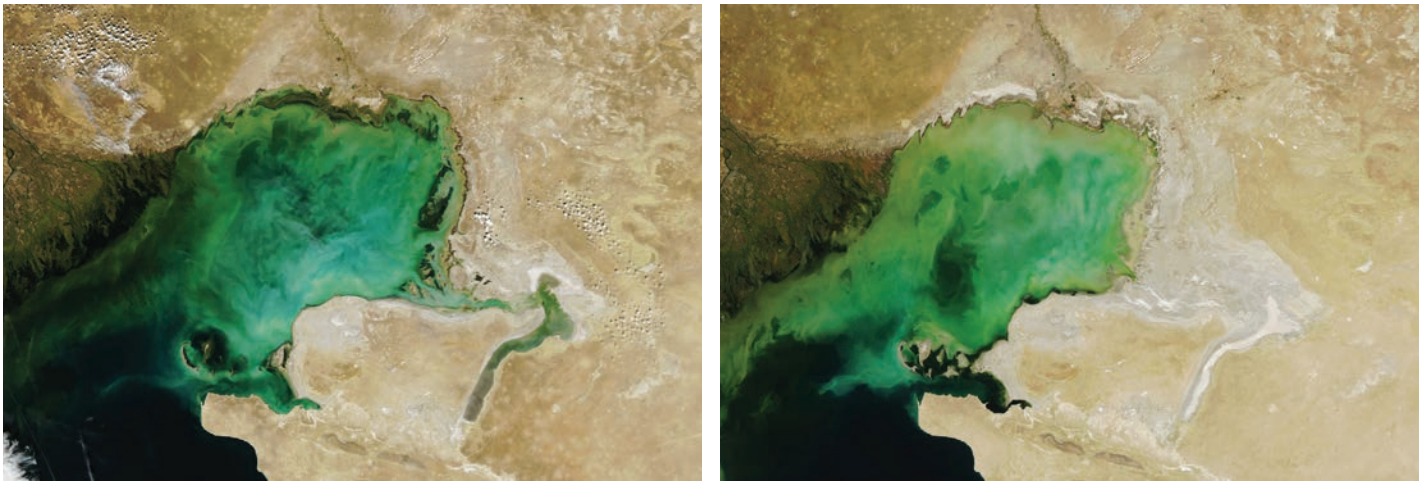
But that shift was not uniform throughout the reserve. Areas that were uplifted, as revealed by the Sentinel data, appeared to enhance coastline retreat from falling water levels, whereas areas of subsidence offset it, at least in part.

Identifying the causes of the subsidence and uplift could help disentangle the relative contributions of tectonics and humans to the changing coastline. The region's uplift could be due to some actively deforming folds related to the nearby Caucasus Mountains, Fielding said. Both the Caucasus and the Caspian Sea are within a convergence zone where the Arabian and Eurasian tectonic plates are colliding.

The uplift was surprising because the area is generally very flat, Fielding said. "There's not much of a ridge at the surface. We wouldn't look at it and immediately say, 'Well, that's an active fold,'" he explained.

The flat landscape means there's likely something else causing the uplift, according to Ian Pierce, a geologist at the University of Oxford who was not involved in the new study. If the rates measured by the research team had persisted for thousands of years, as fold deformation typically does, tall landforms would have appeared.

The subsidence rates measured by the team, on the other hand, are in line with



In the past few decades, water levels in the Caspian Sea have dropped rapidly. These images of the sea's northern shore taken by NASA's Aqua satellite show the change between 2006 (left) and 2022. Credit: NASA Earth Observatory

what scientists would expect on the basis of measurements from other subsiding coastal regions, said Timothy Dixon, a geophysicist at the University of South Florida who was not involved in the study.

Pierce said he suspects that anthropogenic activity—such as water pumping or oil and gas extraction—may have contributed to vertical ground motion. "I just don't think we see those types of magnitudes of rates from just tectonics," he said.

Measuring Azerbaijan and Beyond

Understanding how and why the coastline is changing helps land managers in the Gizil-Aghaj State Reserve predict shifts in habitat conditions and plan their conservation actions accordingly, Bahruz Ahadov, a geophysicist at the Oil and Gas Institute and the Institute of Geology and Geophysics in Azerbaijan and a coauthor of the new research, wrote in an email.

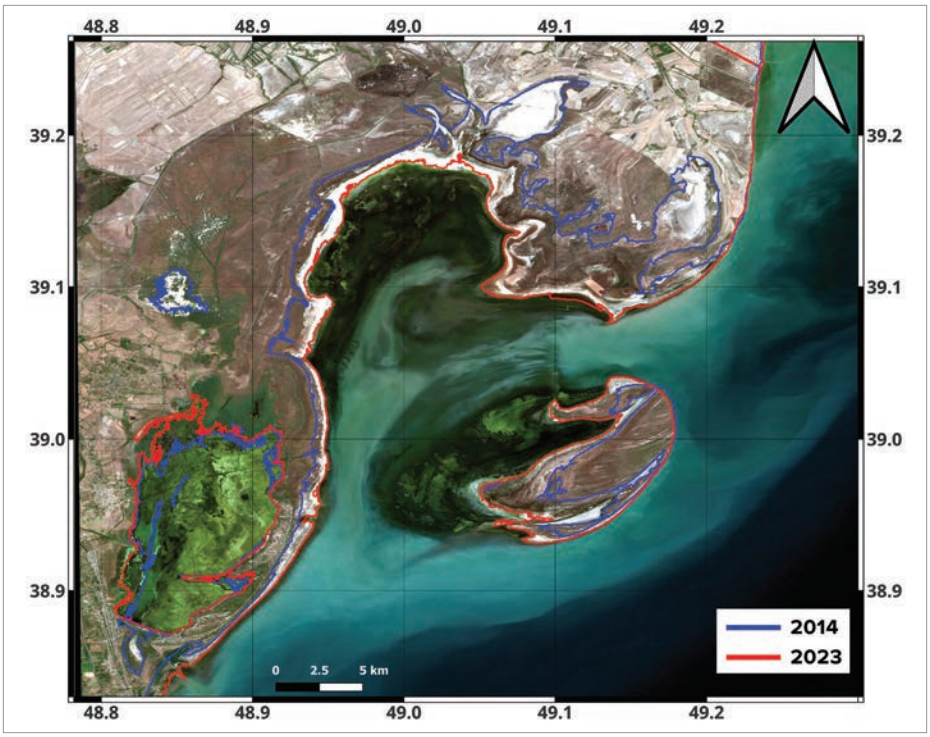
That could involve preparing both ecosystems and human communities living near the Caspian Sea for the potential impacts of sea level changes, Ahadov wrote. Wetlands located on uplifting land will lose water more rapidly than the other parts of the coast, Fielding added.

The findings are "crucial for adapting to environmental changes and ensuring the long-term viability of these coastal areas," Ahadov wrote.

NASA's NISAR (NASA-ISRO Synthetic Aperture Radar) mission, a satellite mission planned to launch in 2024, will provide higher-resolution land deformation data, Dixon and Fielding both said. NISAR will let scientists measure vertical land motion over vegetated landscapes, something that hasn't been possible with data from existing satellites, they said.

"In the areas where we're not able to exploit Sentinel data, the NISAR data will fill in the gaps," Dixon said.

"It's important to keep these vertical land motion measurements going to better understand how the land is moving relative to water levels, both in Azerbaijan and around the world," Fielding said. "We're really looking forward to getting these data."



Between 2014 and 2023, the coastline of Azerbaijan's Gizil-Aghaj State Reserve shifted to reveal an additional 218 square kilometers (84 square miles) of land. Credit: Bahruz Ahadov, Eric Fielding, and Fakhraddin Kadirov

By **Grace van Deelen** (@GVD__), Staff Writer

National Science Board Reports a Need for More Support of STEM Talent

In the United States science, technology, engineering, and mathematics (STEM) education, research, and development need more funding and support to remain competitive on a global scale, according to a federally mandated report evaluating the country's global position in science and engineering.

The report found that though the United States leads the world in research and development funding, at about $800 billion, other countries are catching up, making additional U.S. support of domestic STEM talent ever more important. The Science and Engineering Indicators report is released every 2 years by the National Science Board, which governs the U.S. National Science Foundation (NSF) and advises Congress and the president on science policy (bit.ly/SE-Indicators).

"For the U.S. to maintain leadership in science and technology, and the societal and economic impacts that result, we must invest in and accelerate our commitment to STEM," said NSF director Sethuraman Panchanathan in a statement.

The report emphasized that flat federal funding for research and development is creating a crisis-level shortage of support for domestic STEM talent that has increased the country's reliance on scientists and engineers from abroad. Overall, workers born outside the United States accounted for 19% of the country's STEM workforce in 2021.

As other countries increase support of STEM workers, the United States risks losing those workers, too, said Maureen Condic, chair of the National Science Board's Committee on National Science and Engineering Policy and a neurobiologist at the University of Utah, at a press conference. "It's not a given that the U.S. will continue to attract and retain highly competent international STEM talent," she said.

Together developing and retaining STEM talent is an "incredibly important piece of the puzzle," said Matt Hourihan, associate director of research and development at the Federation of American Scientists, a policy research and advocacy organization. "There are smart and talented scientists and engineers all over the world," he said. One key to keeping the nation competitive on a global scale is "pursuing policy actions that continue to make us the most attractive place for talent."

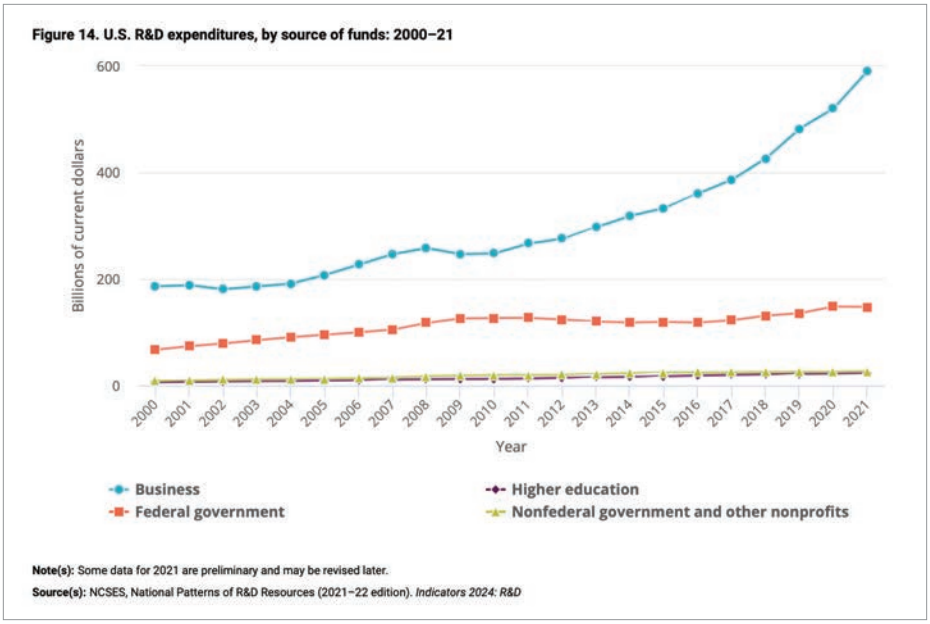
"For the U.S. to maintain leadership in science and technology, and the societal and economic impacts that result, we must invest in and accelerate our commitment to STEM."

The report also noted that though spending on research and development is high in the United States, most of that spending comes from businesses rather than from the federal government. In 2021, 75% of research and development expenditures came from private sources.

Investments from both the private and public sectors are important for long-term competitiveness, but they serve different purposes, Hourihan said. The results of publicly funded research tend to be more accessible to the public, whereas industrial research isn't always widely shared. That can limit collaborations and the free flow of scientific ideas, he explained. Public and private investments "are not substitutes for each other," he said. "They're complements."

The report's authors said in a statement that the United States must appropriate robust funding to federal science agencies and take advantage of policies such as the 2022 CHIPS and Science Act to ensure that the country remains competitive.

President Joe Biden's proposed budget for fiscal year 2025 includes some increases for federal research agencies, but Congress will have the final say on how money is spent. The CHIPS and Science Act authorized up to $35 billion in funding for science agencies, but Biden's proposal asks for just $20 billion, disappointing some science advocates, *Nature* reported (bit.ly/Biden-science-budget).



The United States leads the world in research and development spending, but most of that funding comes from businesses rather than from the federal government. Credit: NSB/NSF Science and Engineering Indicators 2024

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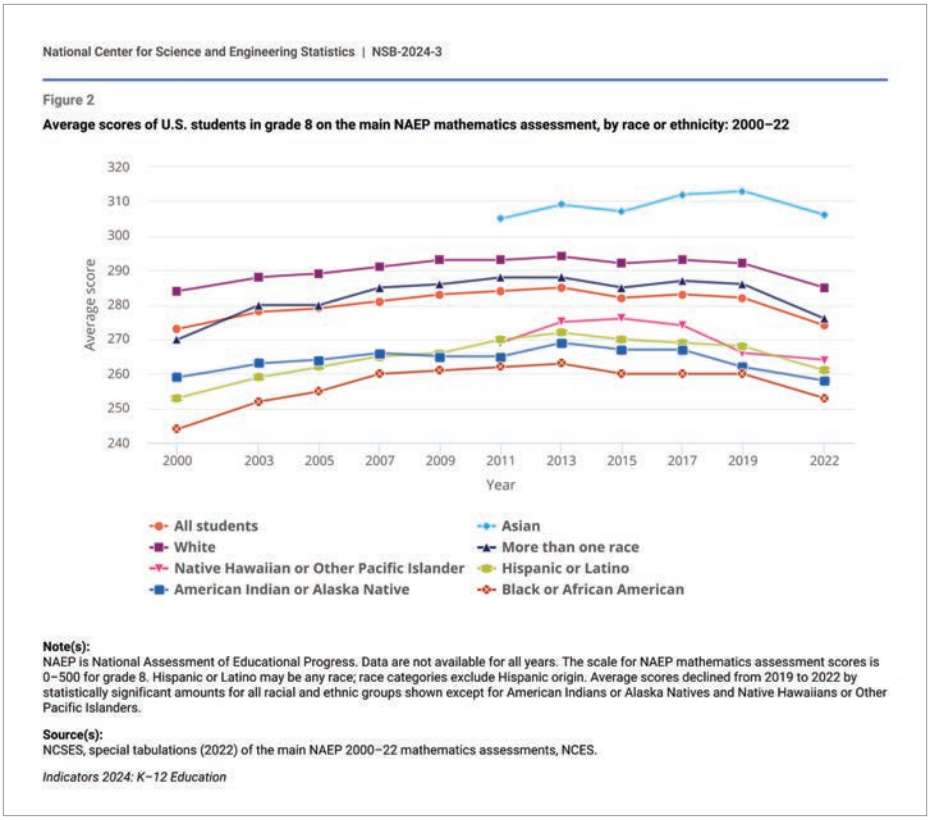
Students from two Florida schools participate in a briefing as part of NASA's NextGen STEM project. Credit: NASA/Kim Shiflett



Scores on a national mathematics exam have dropped since the COVID-19 pandemic. Credit: NSB/NSF Science and Engineering Indicators 2024

Dropping Scores

The report also highlighted that mathematics scores for American students are also slipping: From 2020 to 2023, the average math assessment score for 13-year-old students dropped by 9 percentage points.

The gap between the highest and lowest-scoring students in mathematics has widened as well and is now the largest it has been since the assessment began in 1978. The report named the COVID-19 pandemic as one of the causes of the drop, although test scores in math and science have stagnated for years.

"It's not a given that the U.S. will continue to attract and retain highly competent international STEM talent."

Black students, American Indian students, and students eligible for free or reduced-cost school lunch had the largest drops in mathematics scores from 2020 to 2023. Those discrepancies extend into higher education as well: Hispanic or Latino, Black, and American Indian students are underrepresented among science and engineering degree recipients, according to the report.

"The nation must rapidly recruit, train, and retain diverse STEM educators, particularly for underserved student populations and school districts," Condic said at the press conference.

A major barrier to cultivating STEM talent in the United States is the expense of higher education. A National Science Board policy brief based on the new report recommended making higher education more accessible by increasing scholarships for low-income students, investing in community colleges and minority-serving institutions such as historically Black colleges and universities, and increasing Pell Grant amounts, among other actions. For doctoral students, increased stipends and additional benefits are needed, according to the brief.

"Investment in education at all levels is greatly needed in our country," Condic said at the press conference.

By **Grace van Deelen** (@GVD__), Staff Writer

A Magma Ocean Fuels This Exoplanet's Atmosphere

55 Cancri e, illustrated here, is a lava world with an outgassed atmosphere. Credit: NASA, ESA, CSA, R. Crawford (STScI), CC BY 4.0 (bit.ly/ccby4-0)

For the first time, astronomers have discovered an atmosphere surrounding a rocky exoplanet—but it isn't the atmosphere that the planet started with. Scientists used the James Webb Space Telescope (JWST) to measure the light emitted by 55 Cancri e, a nearby lava world about twice the size of Earth. The data suggest that the atmosphere is thick and possibly has carbon monoxide (CO) and carbon dioxide (CO_2).

"Through observation of this extrasolar example of atmosphere–magma interaction, we can better understand how the early solar system worked," explained Renyu Hu, a planetary scientist at the California Institute of Technology in Pasadena.

First Super-Earth's Second Atmosphere

Discovered in 2004, 55 Cancri e is the smallest and innermost of five known planets orbiting a star 41 light-years away. It was the first known super-Earth, or a rocky planet slightly larger than Earth. The planet is inhospitable to life as we know it: It orbits around its star in less than 18 hours and is a scorching 2,000 kelvins (1,727°C).

As the first known super-Earth, 55 Cancri e has been a top target for observations for 2 decades. Past research revealed that its surface is likely covered in lava and it lacks an atmosphere of hydrogen and helium—a so-called primordial atmosphere that the planet would have been born with.

Astronomers have measured large variations in the planet's emitted heat which could indicate that the atmosphere's chemistry, and thus its heat output, changes rapidly. Or they could suggest that the planet is a bare rock and the heat variations result from differences in the dayside- and nightside lava.

Hu and his colleagues wanted to leverage JWST's powerful infrared capabilities to observe the planet's emitted heat in more detail and reveal more about its potential atmosphere. The team gathered data from the telescope's Near-Infrared Camera (NIRCam) and Mid-Infrared Instrument (MIRI) in November 2022 and March 2023, which provided a clear look at the heat emitted by the planet at different infrared wavelengths.

"The atmosphere is supported by the magma ocean down below."

The new data also indicated that 55 Cancri e's thermal spectrum has none of the emissions features expected of a primordial hydrogen-helium atmosphere. If it ever had one, it was probably quickly blown away by stellar winds.

The team's simulations of 55 Cancri e's atmosphere, which were tested with different chemical combinations, temperatures, and pressures, provided context to the new JWST data. The spectrum doesn't match what would be expected from an atmosphere of vaporized rock but does suggest that 55 Cancri e could have a thick secondary atmosphere made of CO and CO_2 and other volatiles outgassed from its volcanic surface.

"We envision that the atmosphere is supported by the magma ocean down below," Hu said. "The magma ocean is likely to be a highly dynamic environment, and the interaction between the magma ocean and the atmosphere could result in the composition of the atmosphere changing quite quickly."

Those interactions could also release rock-forming elements such as sodium, magnesium, and silicon into the atmosphere, which would alter the atmospheric structure and explain the variability of past observations, Hu said. This research was published in *Nature* (bit.ly/55-Cancri-e-atmosphere).

Beyond the Cosmic Shoreline

"This study convinces me that something interesting is going on on this planet and that repeated observations and analyses are needed," said Peter Gao, especially because the planet has shown heat variability in the past.

Gao, an exoplanetary scientist at the Carnegie Institution for Science in Washington, D.C., who was not involved with the work, said that demystifying 55 Cancri e's atmosphere could help astronomers understand the "cosmic shoreline" of exoplanets. This concept describes how planets with too much heat or without enough gravity, like Mars, lose their atmospheres too quickly for life to develop.

Confirmation of 55 Cancri e's secondary atmosphere, Gao said, "would show that there exists an additional 'shoreline'—the opposite shore, if you will—where at high enough temperatures the surface becomes molten, allowing interior volatiles to outgas onto the surface to form an atmosphere."

Hu added that both Earth and Venus may have looked like 55 Cancri e a few billion years ago: volatile lava worlds covered by magma oceans that generated outgassed atmospheres. The atmosphere of 55 Cancri e could provide new insight into our solar system's past and also about other lava worlds that may or may not resemble the first super-Earth.

"I guess we should observe more of them!" Gao said.

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

The Tonga Eruption Left Deep-Sea Life Buried in Ash

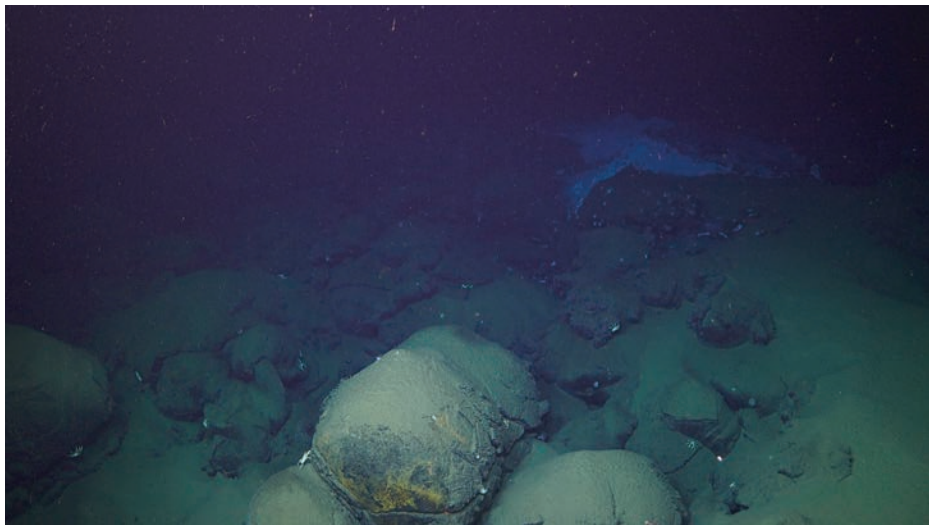
In April 2022, scientists were on a research vessel in the Lau Basin near Tonga to study the animals that live around hydrothermal vents in the deep sea. But when they lowered a remotely operated vehicle (ROV) to search for the critters, they found the seafloor, normally a hard basalt surface, blanketed in sediment. They could see few snails and mussels.

"It was like a snow-covered landscape," said Roxanne Beinart, a marine microbial ecologist at the University of Rhode Island who was on the expedition.

Beinart and her colleagues suspected that they were looking at a coating of ash from the January 2022 eruption of the Hunga volcano, one of the most powerful eruptions ever recorded. The ashfall had completely transformed the ecosystem, killing off vulnerable mollusks.

The researchers recognized that they had a rare opportunity to document the effects of a volcanic eruption on marine ecosystems. Their initial findings were published in *Communications Earth and Environment* and intend to track the recovery of these ecosystems through time (bit.ly/Hunga-hydrothermal-life).

"This is a real opportunity to understand and to study the impacts of a large eruption—where we understand what happened, where we know the processes, we know the timescales involved—and to understand the impacts on the seafloor," said Isobel Yeo, a volcanologist at the United Kingdom's National Oceanography Centre who wasn't involved in the study.



Researchers aiming to study seafloor snails and mussels at hydrothermal vents near Tonga in April 2022 arrived at their study site (seen here) to find the seafloor covered in ash from the eruption of the Hunga volcano. Credit: Beinart et al., 2024, https://doi.org/10.1038/s43247-024-01411-w, CC BY 4.0 (bit.ly/ccby4-0)

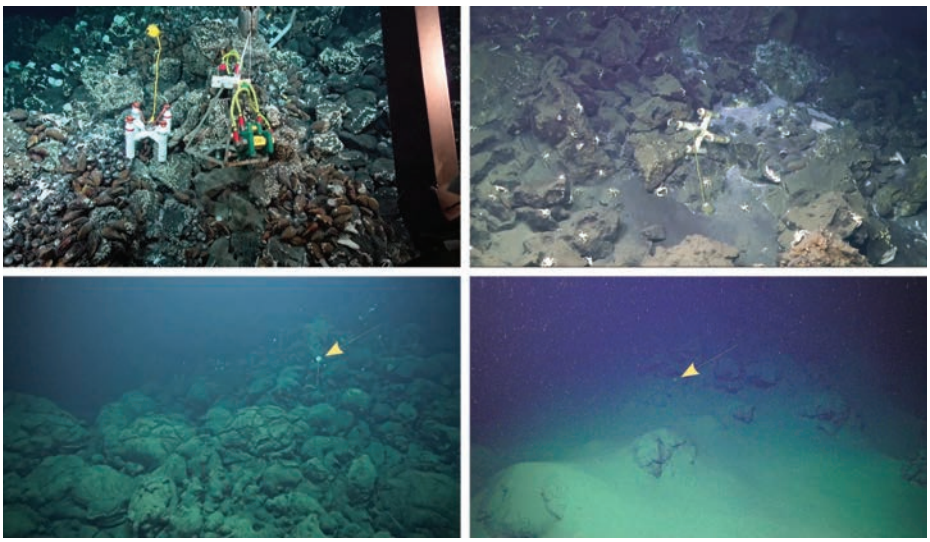
An Avalanche of Ash

Over 24 days, the scientists used the ROV to survey six hydrothermal vent fields and scoop up samples of sediment. Under the microscopes aboard the ship, "you could pretty quickly and easily see that it was just full of glass," said Shawn Arellano, a marine ecologist at Western Washington University and a coauthor of the study. Fine grains of glass are a telltale characteristic of volcanic ash.

To see how deep the ash was, the group improvised a ruler by drawing colored marks on a long, T-shaped metal rod that the clawed arm of the ROV could hold. The ash was found to be up to 1.5 meters (~5 feet) deep at the sites closest to the volcano. And even 96 kilometers (60 miles) away, the ash at one site was still nearly 0.5 meter (~2 feet) deep.

After the eruption, the ash likely dropped from the sky and sank in the water. The researchers think that as it landed and trickled down the volcano's submerged slopes, it picked up sediment and became denser, causing it to gain speed, like a snow avalanche does on land. The flow was able to "roar into the deep sea," said Mike Clare, a marine geoscientist also at the National Oceanography Centre in the United Kingdom who wasn't involved in the study.

The ash had to travel over undulating terrain to reach the hydrothermal vents—a testament to how powerful the currents were. "One of the surprises of the study is that despite this irregular seafloor relief, the flows



The researchers observed the eruption's impact on sea life by comparing footage from an expedition before the eruption in 2019 (two photos at left) with footage taken after the eruption in 2022 (two photos at right). Credit: Beinart et al., 2024, https://doi.org/10.1038/s43247-024-01411-w, CC BY 4.0 (bit.ly/ccby4-0)

have been able to overcome this distance," Clare said.

Buried Alive

All that ash had a dramatic effect on marine ecosystems.

The scientists knew of an expedition that had visited the same hydrothermal vent sites in 2019, so they compared footage from that expedition with footage from their ROV. The contrast was stark.

Some animals such as lobsters and crabs were crawling around in their videos, their

"Those populations [of snails and mussels] were decimated."

populations not affected by the ash, but the snails and mussels they had come to study, many of which are endangered or vulnerable species, had taken a hit. "Those populations were decimated," Beinart said.

Beinart and her colleagues suspected that the mollusks were the most affected in part because they are less mobile. Mussels, for example, extend strong fibers that attach to a hard surface so they can "pull themselves along like Spiderman," Arellano said. These organisms' metabolisms also require a symbiotic relationship with bacteria, and that relationship requires a lot of oxygen. When the ash landed on these animals, their need for oxygen outpaced their ability to escape from under the ash, and they suffocated.

The researchers will return to the region in 2026 to track the changes to the hydrothermal vent sites. "We're focused on trying to understand the recovery of these systems and the dynamics of how they might cope," Beinart said.

Clare noted that scientists know from other regions with volcanic activity that this ecosystem will recover, but how quickly that will happen and how it will play out are unknown. "Whilst this study is a really valuable and useful one, I suspect its value as a baseline will become apparent over the coming decade as we start to revisit and see how the seafloor changes," he said.

By **Andrew Chapman** (@andrew7chapman), Science Writer

How Sticky Is It Outside?

The U.S. National Weather Service's WetBulb Globe Temperature is used to determine safety levels for people working in direct sunlight. It's a way to measure heat stress on the human body and includes data on temperature, humidity, wind speed, Sun angle, and cloud cover.

Although metrics such as this are more holistic than 1D measures such as humidity or the ambient air temperature available with a standard thermometer (also known as dry-bulb temperature), they have their own limitations. Some types of heat feel different than others and affect the human body in different ways.

In a new study published in the *Journal of the Atmospheric Sciences*, researchers outlined a new metric to address that shortcoming (bit .ly/stickiness-variable). And it will sound relatable to anyone who's ever been outside on a hot summer day: stickiness.

Casey Ivanovich, a doctoral student in climate science at Columbia University in New York, was researching climate extremes around the world. The scope of her research included the Persian Gulf region, which is extremely hot and generally dry, and Bangladesh, which has higher humidity but lower dry-bulb temperatures. "These are two different types of extremes that might have the same measurement on a wet-bulb temperature thermometer," she said.

A wet-bulb temperature is read from a thermometer covered in a wet cloth. It conveys the temperature a person feels as their sweat evaporates and cools their skin and is

"Not all wet-bulb temperatures are created equal."

affected by humidity. Wet-bulb temperature is one of three measurements that factor into a WetBulb Globe Temperature estimate. (The others are a shaded dry-bulb temperature and solar radiation.)

Stickiness quantifies how heat and humidity contribute to humid heat, seeking to explain why two types of heat that feel so

different can have the same wet-bulb temperature.

Nutritional value is a similar concept. Metrics such as volume and carbohydrate levels can explain why two dishes with the same number of calories, such as a small serving of pasta and a much larger serving of zucchini noodles, can feel so different to eat.

Ivanovich compared stickiness to "spice," a term used in oceanography to convey the relative contributions of temperature and salinity to water density. Using the same derivation as a classic paper about spice (bit.ly/spice-variable), Ivanovich and her team created the new stickiness variable by factoring in wet-bulb temperature, humidity, and dry-bulb temperature. Stickiness is designed to be most responsive to changes in humidity and dry-bulb temperature and to be less correlated with changes in wet-bulb temperature.

Jane W. Baldwin, a climate scientist at the University of California, Irvine, who researches the effects of heat on human health, said she was excited to see this study come out because "not all wet-bulb temperatures are created equal."

For instance, a day with a high dry-bulb temperature and low humidity levels could have the same wet-bulb temperature reading as a day with a lower dry-bulb temperature and higher humidity levels. But physiological studies have shown that the former presents a greater risk of heat stroke, because under such conditions, the human body can't sweat enough to maintain a thermal equilibrium.

"I think stickiness will help us in the long run understand how equivalent levels of wet-bulb temperature might lead to different pathways of adverse health outcomes," Baldwin said.

"Places that have higher variation in stickiness might be places where we're more able to disentangle the separate impacts of temperature and humidity."

Humidity's Role in Human Health

Ivanovich said she envisions stickiness being most useful for heat stress preparedness planning, especially as extreme heat becomes more commonplace globally. But, she added, it could also clear up a confusing disparity between physiological and epidemiological findings.

Physiologically, humidity should worsen heat stress for humans by inhibiting sweat evaporation (the main way humans cool themselves), but many population-scale epidemiology studies suggest that the most important predictor of mortality is simply dry-bulb temperature (bit.ly/temperature-mortality). That is, tracking humidity doesn't help scientists more effectively predict human health effects, including mortality.

"That's kind of unexpected," Ivanovich said. But these studies may be biased toward outcomes in Western countries, which tend to have more reliable mortality data, she explained. In these regions, it's more common for heat and humidity to be positively correlated, that is, for the same days that exhibit extreme heat also to have high humidity. Some local-level weather stations or governments may choose to track only heat, and it can be difficult for epidemiological researchers to disentangle the effects of heat and humidity.

Ivanovich suggested that tracking stickiness could help researchers learn more about how humidity affects people in places that have both extreme dry heat days and extreme humid heat days, such as western Mexico, the Arabian Peninsula, and Australia.

Baldwin suggested that the inverse could be useful as well, meaning that researchers could use stickiness to determine the most useful places from which to gather data. "Places that have higher variation in stickiness might be places where we're more able to disentangle the separate impacts of temperature and humidity, and so [those] could be places to target gathering epidemiological records from to help reconcile the role of humidity in heat-related mortality," she said.

By **Emily Dieckman** (@emfurd), Associate Editor

Opposite: Chris Yarzab/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Antarctic Ice Doughnuts May Hold the Key to Shelf Collapse

This image is the first direct observational evidence of ring fractures forming around a meltwater lake in Antarctica. Credit: Alison Banwell

The Antarctic summer of 2019–2020 was the most exceptional melt season on record for the George VI ice shelf. But no one could get there to study ice shelf processes because of the COVID-19 pandemic.

Alison Banwell, who had placed cameras and monitors there in November 2019 to capture the filling and draining of a meltwater lake, was one of the sidelined researchers. When she returned 2 years later, after the exceptional melt season and an extra winter of exposure, "lots of the instruments were totally encased in ice," she said.

But a time-lapse camera survived, providing the first on-the-ground images of ring fractures. These circular cracks in ice shelves had been predicted, simulated, and even observed by satellite, but "until now, no one had any actual in situ evidence of that [style of] fracture," Banwell said.

The research is the latest step by Banwell, a glaciologist at the University of Colorado Boulder, and her colleagues in deciphering what triggers ice shelves to rapidly collapse.

In 2013, the researchers proposed that ring fractures contributed to the breakup of the massive Larsen B ice shelf in 2002 (bit.ly/Larsen-B-ring-fractures). In 2019, they published evidence of ice sheets flexing under the weight of meltwater lakes (bit.ly/ice-sheet-flexure). Now, in the *Journal of Glaciology,* they've shared the first direct observations of meltwater lakes leading to ring fractures (bit.ly/meltwater-ring-fractures).

Flex and Fracture

The mechanics of ring fractures are straightforward. As meltwater pools in low points, it weighs down the ice, like a person standing on a trampoline. These lakes grow gradually but can drain quickly. If the water punches through to the ocean below and drains, the ice shelf rebounds rapidly and fractures in the process. That can set off a chain reaction: New ring fractures drain nearby lakes, which trigger further fractures.

This process may have caused the rapid shattering of the Larsen B ice shelf, a 12,000-year-old slab the size of Rhode Island that disintegrated in just 35 days. "The most important fracture in Larsen B was this ring fracture," Banwell said, referring to simulations of the breakup.

The newly published images of ring fractures come from a doline on the George VI ice shelf, attached to the Antarctic Peninsula. A doline is a drained lake basin that looks like a massive ice doughnut, with an uplifted rim encircling a central depression. As the air temperature warms, the doline fills with meltwater.

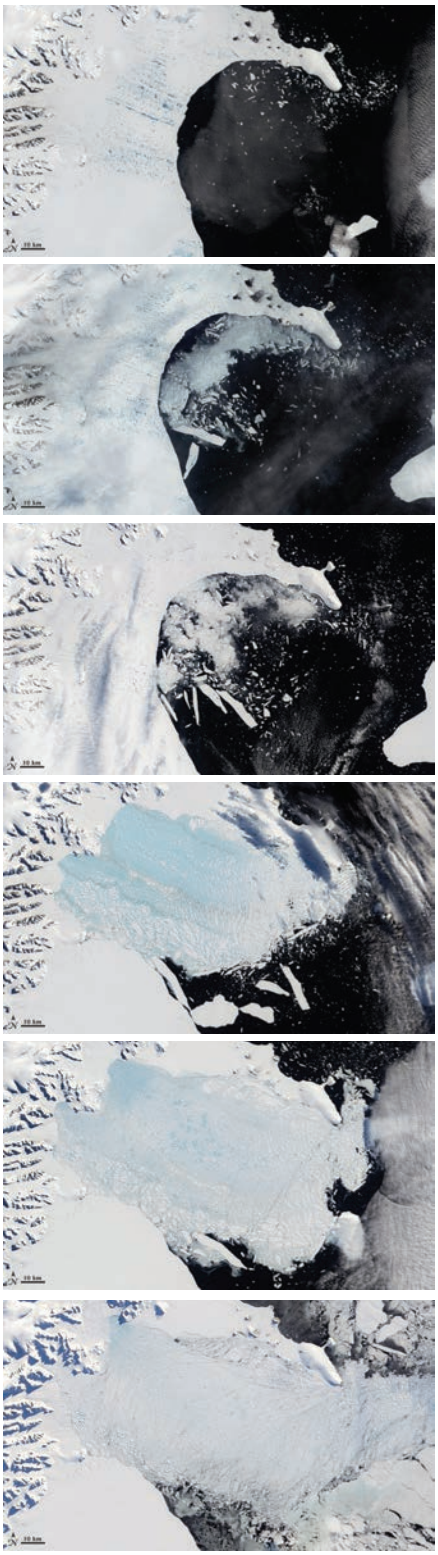
"It's one data point. But that data point is worth a lot, because it's the only one of its kind."

Meltwater ponding is unpredictable. But satellite records showed that this bowl-shaped doline persisted through several melt seasons. Fortuitously for researchers, it was close to the British Antarctic Survey's remote field station on Fossil Bluff.

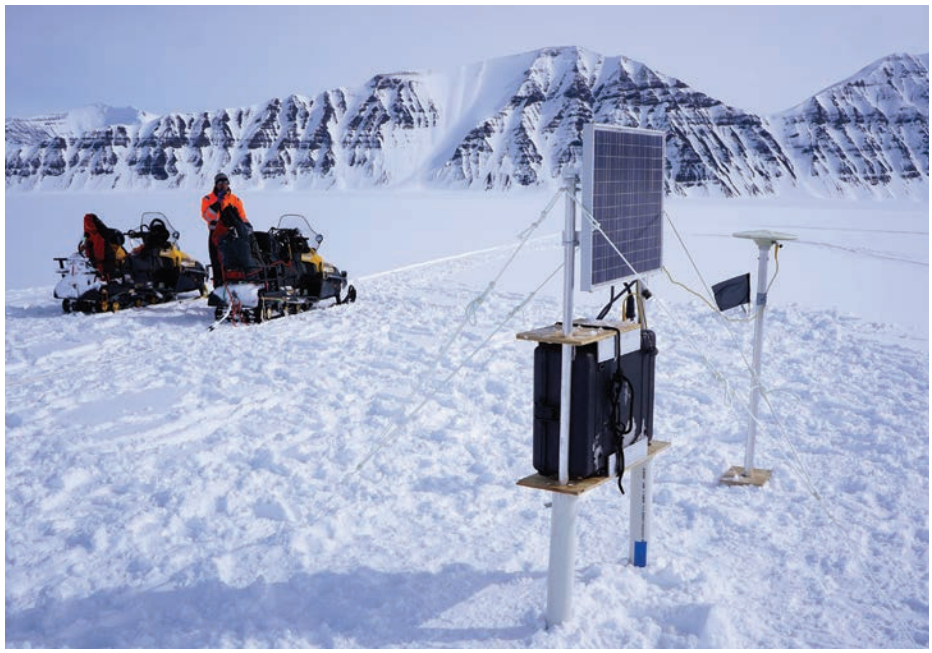
Banwell and her colleagues traveled for more than an hour on tethered snowmobiles to install their monitoring equipment, certain the doline would fill with meltwater again. Their equipment included a camera, four GPS stations, a temperature gauge, and pressure sensors to determine the volume of the anticipated lake.

When pandemic-related travel restrictions eased 2 years later, the team could salvage only two GPS stations and the time-lapse camera, which had snapped images every 30 minutes for the first 4.5 months.

The images showed that melting started in early December 2019. Ring fractures appeared by late December, framing the banks of the lake.



The Larsen B ice shelf collapsed in a little over a month in 2002, as seen in this sequence of satellite images. Credit: MODIS images from NASA's Terra satellite supplied by Ted Scambos, National Snow and Ice Data Center, University of Colorado Boulder



Banwell and her colleagues installed equipment in and around a doline on the George VI ice shelf to record a ring fracture developing. After an exceptional melt season and an unplanned overwintering, only two GPS stations and a camera were salvageable. Credit: Alison Banwell

Ringing Endorsements

Antarctica's melting ice shelves can indirectly lead to sea level rise, but simulations of future collapse are needed to know where, when, and how much melting will occur. The new images improve our understanding of ice processes.

"The most important fracture in Larsen B was this ring fracture."

On-the-ice observations are essential for simulating ice shelf stability, said Amber Leeson, a glaciologist at Lancaster University in the United Kingdom who was not involved in the research.

Though satellites have recorded ring fractures in the past, "you really need real-world, ground truth examples to constrain the modeling," she said. This study illuminates the timeline and the magnitude of change which can't be fully captured by satellites, she added, and helps modelers make predictions based on the best possible understanding of ice physics.

"It's one data point," Leeson said of the new study. "But that data point is worth a lot, because it's the only one of its kind."

Though most of the research equipment was lost to the ice, the study still provides relevant, useful data, said Lauren Andrews, a glaciologist at NASA Goddard Space Flight Center not involved in the new study. "This is a really nice example of how straightforward observations can provide insight into ice processes," she said.

There's obvious work remaining. The lost pressure sensors would have estimated lake volume, for example.

Also, the relatively stable George VI ice shelf is wedged between two landforms. The process may be different on less constrained sheets such as Larsen B.

What is clear is that when meltwater lakes form, ring fractures can follow. Because hundreds of lakes freckled Larsen B, hundreds of ring fractures could have caused the collapse, as Banwell and her colleagues theorized more than a decade ago. The new study "has shown that it's a very plausible explanation," Leeson said.

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

Cosmic Rays Shed Light on Stone Age Timelines

The eastern Mediterranean was the setting of major transitions in the late Stone Age, including the widespread adoption of farming. But tracing the timelines of those transitions is difficult. Now, researchers have dated a late Stone Age (Neolithic) settlement in Greece using a combination of tree ring counting and radiocarbon dating (bit.ly/Neolithic-settlement-dating).

The group measured radiocarbon in timber samples from Dispilio, where early farmers built houses on stilts along a lakeshore. A radiocarbon spike traced to a known solar storm in 5259 BCE enabled the team to date the settlement with single-year precision.

"Thanks to the painstaking work of these authors, Dispilio is the first site from the Neolithic in the northern Balkans and Greece with an exact absolute timeline," said Brita Lorentzen, an environmental archaeologist at the University of Georgia in Athens, Ga. who was not involved with the study.

The results provide a chronological reference point for other prehistoric sites in the Mediterranean and may inform research about how early farmers interacted with their environment.

Prehistoric farmers lived in elevated houses on Lake Orestiada in Greece, like those re-created here. Credit: George Pachantouris/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

"Combining tree rings and radiocarbon of Miyake events is a bit like getting the cheat codes in a video game."

Tree Rings Record the Past

Archaeologists who study the time before written history must rely on other types of records. Where wooden artifacts are available, those records can be found in tree rings.

Each ring records the plant's annual growth. Wet years promote growth and produce thick rings, whereas dry years produce thinner rings. Because neighboring trees experience similar weather conditions, their yearly rings create a local climatic barcode. Scientists can piece together partially overlapping barcodes to create tree ring chronologies spanning thousands of years. When a new wood sample is collected, its rings can be matched with established chronologies to determine when the tree died.

The longest existing tree ring records in the United States come from California bristlecone pines and go back almost 9,000 years. Central Europe's tree ring records go back almost 13,000 years. But such long records are rare.

"Instead of one continuous chronology going from the present back to 5000 BC, we may instead have several chunks," Lorentzen explained. These chunks are said to float. Radiocarbon ages from the Neolithic have uncertainties of decades or more, so chunks of single-year tree ring records need additional constraints to narrow down the period they cover.

A Chronological Cheat Code

Because there is no continuous tree ring record for the Mediterranean reaching into the Neolithic, the new study's authors initially faced a floating chronology. But cosmic rays illuminated the problem.

The researchers made use of so-called Miyake events: short, intense bombardments of cosmic rays likely caused by massive solar storms. At least five Miyake events have been discovered in Earth's past, dating from the 8th millennium BCE to 993 CE. If such an event happened today, it could disrupt satellite and electrical signals and produce aurorae far outside the Arctic Circle.

It is convenient for dendrochronologists that Miyake events cause rapid increases in atmospheric radiocarbon, which is incorporated into plants. Unlike the thick or thin patterns of tree rings, which depend on local climate conditions, the radiocarbon spikes produced by Miyake events are global. This eliminates the need for a regional dendrochronological record.

"Combining tree rings and radiocarbon of Miyake events is a bit like getting the cheat codes in a video game," Lorentzen said. "Instead of build[ing] one continuous, long chronology extending back from the present, we can skip that and anchor a chunk of

chronology like that from Dispilio to an exact point in time."

To date wood from Dispilio, the study's authors made use of a previously known Miyake event in 5259 BCE. Conventional radiocarbon dating suggested that the trees had been felled in the mid-6th millennium BCE. The researchers then homed in on each tree ring and searched for the Miyake peak, which they found in multiple samples.

"Each of the tree rings in this chronology provides an annual time capsule of the climate and environmental conditions."

Connecting Climate, Farming, and Construction

Using the Miyake peak as a reference point, the researchers determined that Dispilio was occupied for at least 188 years from 5328 to 5140 BCE, with intermittent construction during that time.

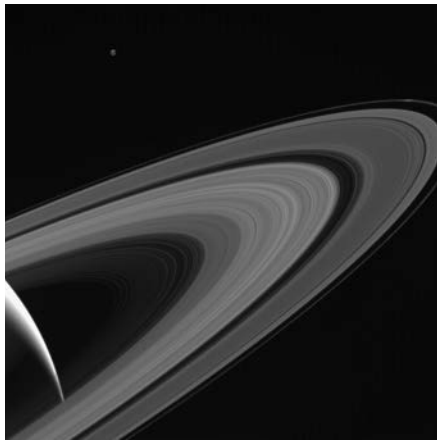
"This is the first time that we get annually resolved information on construction episodes on a 6th millennium BC site," said Andrej Maczkowski, an archaeologist at the University of Bern, in Switzerland, and first author of the study. In the future, tree ring sequences from Dispilio could be used to precisely date other Neolithic sites in the Mediterranean.

Wood samples from Dispilio can also provide insights into prehistoric climate, Maczkowski explained. Because a tree ring's width reflects annual rainfall, scientists can search the dendrochronological record for signs of drought and study how early farmers coped with such crises. Conversely, tree ring records can be combined with archaeological and climate information to reveal how agriculture affected the environment.

"Each of the tree rings in this chronology provides an annual time capsule of the climate and environmental conditions," Lorentzen said. "So we can look very precisely at both human and climate activities over time and see how they fit together."

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

Distant Stars Spotlight Mini Moons in Saturn's Rings



Saturn's rings have gaps big and small. The larger ones can be seen in this 2017 image taken by NASA's Cassini spacecraft. Credit: NASA/JPL-Caltech/Space Science Institute

The rings of Saturn have fascinated skywatchers for centuries, and scientists are still finding tiny gems hidden in the icy dust. Using data from the Cassini spacecraft, researchers studying one of the rings recently uncovered gaps just a few tens of meters wide that they believe surround unseen mini moonlets. These regions of empty space might be smaller versions of structures spotted previously in one of Saturn's larger rings.

In the predawn hours of 15 October 1997, a Titan rocket lifted off the launchpad at Florida's Cape Canaveral. After nearly 7 years and multiple gravity assists from Venus, Earth, and Jupiter, the Cassini spacecraft and Huygens probe arrived at Saturn, a journey of more than 3 billion kilometers (2 billion miles). From 2004 to 2013, onboard instruments collected data about the Saturnian system and beamed the measurements back to Earth.

In addition to capturing more than 450,000 images of the Saturnian system, the spacecraft inadvertently tracked distant stars peeking through Saturn's rings. These observations turned out to be useful for studying the rings themselves.

A star viewed that way is basically functioning like a searchlight behind the rings, said Richard Jerousek, a planetary astrophysicist at the University of Central Florida in Orlando and a member of the Cassini Ultraviolet Imaging Spectrograph team from 2008 to 2017. "We get a measurement of how much starlight passes through," he said.

Jerousek and his colleagues recently analyzed data from those "occultations" collected by the Ultraviolet Imaging Spectrograph. By aggregating those data, the researchers assembled a 2D map revealing the relative transparency of different parts of Saturn's rings.

Such a map can reveal hitherto unseen details in Saturn's rings, said Frank Spahn, a theoretical physicist at the University of Potsdam in Germany not involved in the research. "The dimming gives you an image of the structure," he said.

There's also a big advantage to using occultation data rather than simply taking a picture of Saturn's rings, Jerousek said. Occultation observations can reveal features as small as about 100 square meters (1,100 square feet). That's about one nine hundredth the area of a pixel in the highest-resolution images returned by Cassini, he said.

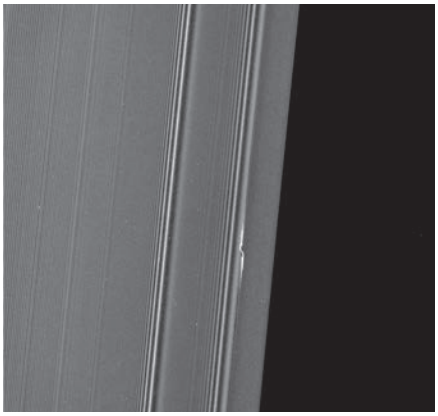
"We get a measurement of how much starlight passes through."

Spotting Aircraft

The researchers spotted dozens of places in Saturn's C ring—one of its innermost rings—that appeared to be 100% transparent. Those regions were small, the team inferred: just a few tens of meters wide in the radial direction and 5–10 kilometers long in the azimuthal direction.

Their elongated geometry was a tip-off to their potential identity—similarly shaped structures, albeit much larger, have been spotted in the outer regions of Saturn's A ring. Known as propellers, those features are big enough to show up in Cassini imagery rather than just in occultation data, Jerousek said.

Propellers, as their name suggests, are shaped much like the blades used to propel



The Earhart propeller is visible in this image taken by Cassini. Credit: NASA/JPL-Caltech/Space Science Institute

aircraft and boats. The propellers in Saturn's A ring carry names such as Blériot, Santos-Dumont, and Earhart. "They're named after famous propeller pilots," Jerousek said.

Scientists believe that propellers exist because of unseen moonlets measuring, at most, several hundred meters in diameter. Saturn's rings are made up of an amalgam of icy particles, most of which range in size from centimeters to meters. Moonlets just happen to be a bit larger than average, and their extra gravity contributes to clearing out lobe-shaped regions of space ahead of and behind them in their orbits around Saturn.

"You have two wings," said Spahn. "In the middle, you have the object that causes the structure."

The features in the Cassini-Huygens occultation data are consistent with propellers caused by very small "mini moonlets," Jerousek and his team suggested. Those mini moonlets would be no more than about 20 meters across, the researchers believe, which would make them far more diminutive than the objects that create the named propellers, Jerousek said. "What we're talking about here is much, much smaller scale."

These findings were published in *Icarus* (bit.ly/Saturn-moonlets).

It makes sense that propellers would exist over a wide range of scales, Spahn said. In fact, there are case studies of what happens when moonlets are too large to create propellers and instead create uninterrupted gaps extending 360° around Saturn, he said. "Two moons do that." Those are Pan and Daphnis, and they are both embedded in Saturn's A ring.

The features are consistent with propellers caused by very small "mini moonlets."

A lot of Cassini data remain to be analyzed, but Jerousek and his colleagues are also looking to the future. Uranus, located nearly 1.5 billion kilometers (900 million miles) beyond Saturn, has very faint and thin rings of its own. Exploring Uranus's rings would be a logical next step, Jerousek said. Scientists are rallying behind a flagship mission to Uranus, which has been visited only once before, by Voyager 2 in 1986.

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

Climate Change Threatens 70% of Winemaking Regions

Amy Chen/Unsplash

Seventy percent of the world's winemaking regions could become unsuitable for growing wine grapes if global temperatures exceed 2°C above the preindustrial average. This tally comes from a recent study in *Nature Reviews Earth and Environment* that compiled decades of research exploring the potential impact of climate change on viticulture (bit.ly/climate-change-viticulture).

"The regions that are most threatened are regions that are already hot and dry, because those regions are likely to get both hotter and drier," said Gregory Gambetta, a viticulturist at the Université de Bordeaux in France and a coauthor of the study.

However, vineyards in every region will experience their own set of stressors, from extreme weather to disease, that will make it more difficult to grow grapes and produce wine. "The challenge in one area may not be the challenge in another," Gambetta said.

"The grapevine is a very adaptable plant that has room to grow in a lot of different climates."

New Threats to Old Vintages

Viticulture, or agriculture related to grapevines, is a practice thousands of years old that takes place in almost every region and climate in the world. Growing grapes and producing and consuming wine have become integral to cultural identities and economies.

"The grapevine is a very adaptable plant that has room to grow in a lot of different climates," Gambetta said.

Grape growers have spent centuries figuring out how best to grow grapes and produce wine in their regions, specializing in a few vine cultivars that grow particularly well there. That's why, for example, Argentina is known for its malbec, California its cabernet sauvignon, New Zealand its sauvignon blanc, and France its merlot.

Every region has experienced historic climate shifts, Gambetta said, and has worked out vineyard management strategies to adapt, such as adding irrigation or adjusting how vines are spaced, trained, pruned, or shaded. Regional cultivars have shifted in the past but have remained fairly steady for several decades.

However, as human-driven climate change warms the globe, alters weather patterns, worsens drought, and heightens extreme weather, many vineyards will be pushed to or past their limits.

Gambetta and his colleagues combed through existing research and created a compendium of how global winemaking regions will fare under moderate and extreme climate

Winemaking Regions' Climate Change Risk

Source: van Leeuwen et al, 2024, https://doi.org/10.1038/s43017-024-00521-5
Production statistics: OIV State of the World Vine and Wine Sector in 2022

change scenarios, what the major threats will be, and how each region may adapt to the oncoming hazards.

The researchers found that if global warming climbs higher than 2°C above the preindustrial average, around 29% of current wine regions will experience climate conditions too extreme to grow grapes. An additional 41% may also become unsuitable for viticulture if growers cannot adapt their methods. The emergence of newly suitable growing regions would not offset the loss.

Up to 90% of winemaking regions in the lowlands and coastal areas of Greece, Italy, Southern California, and Spain could disappear by the end of the century.

Excessive heat and water scarcity likely will be felt in most regions. Climate change will intensify adverse grape-growing conditions around the world: Hot will become hotter, dry will become drier, and stormy will become stormier. Grapevine diseases and pests will likely become more prevalent, but their spread is more difficult to predict.

"I was particularly glad to find such a deep analysis of how different interactions with parasites [and] diseases may increase or decrease with climate change," said Ignacio Morales-Castilla, an ecologist at the University of Alcalá in Spain who was not involved with this research. "This is, in my opinion, an expanding field with a huge applied interest that could positively impact growers' decisions."

If warming is capped at 2°C, 25% of current winemaking regions might become more suitable for growing, around 26% are likely to remain at about the same level of suitability, and the remaining 49% would become less suited for wine growing.

A Robust Blend of Adaptation Tools

Just because a region becomes less suitable for viticulture doesn't mean it's impossible to grow grapes there, Gambetta said. Suitability is more of a continuum. A loss of suitability means that more effort and resources are needed to make grape growing viable and productive.

Preserving wine production must be balanced with responsible environmental stewardship.

That could mean introducing or increasing irrigation or carving steppes into mountainsides to grow at milder temperatures. Viticulturists could deploy modular shades during times of peak UV radiation or spray vines with chemicals to ward off pests or diseases. They could adjust vineyard management to make the most of limited water, amend nutrient deficiencies in soil, or plant cover crops to manage the soil's carbon.

Adapting to climate change could also require shifting wine production into newly suitable areas or diversifying grape varietals to include some that would be easier to grow under future climate conditions.

However, regions that might become suitable for wine growing in the future might already be used for other crops or grazing land or for maintaining wild habitats. In such cases, preserving wine production must be balanced with responsible environmental stewardship, the researchers argued.

Moreover, diversifying can be complicated if a region's value in the wine market is tied to a particular kind of grape or flavor, Gambetta explained.

Germany, known for crisp white riesling grapes, could struggle to grow its primary varietal. Many wines are eponymic of their regions: Bordeaux, Champagne, Chianti, and Rioja, to name a few. Pivoting to market other varietals would not be easy.

"Market and tradition and history," Gambetta said, summarizing the challenges for a region to change its vine cultivars. Plus, "they may not have as much flexibility as others to change what they grow because the land that it's growing on is marginal already," he added. Shifting all of that momentum "is easier said than done."

"The economic costs to shift vineyards to higher latitudes or altitudes may not be affordable for most growers," Morales-Castilla added.

The future isn't all doom and gloom, though, Gambetta said. "We're starting with a crop that is pretty robust and adaptable. Suitability in the future is not a black-and-white thing. There's room for adaptation."

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

How Soil Symbionts Could Unlock Climate-Smart Agriculture

From vast cornfields to small rice plots, the way we grow our food and nourish our communities will increasingly bear the brunt of climate change.

Rising temperatures and more extreme weather are exacerbating inequalities in global food systems. More than enough food to feed the global population is already produced, but roughly 783 million people worldwide currently experience hunger as a result of systemic inequalities related to gender, geography, conflict, and resources. Warming of 2°C will drive an estimated 189 million additional people into hunger.

And yet global food production systems are stuck in a vicious cycle that threatens both food security and environmental health.

Farmers in predominantly high-income countries (and elsewhere, when possible) apply vast amounts of inorganic fertilizers to their fields to ensure high yields. Perversely, the synthetic fertilizer supply chain is contributing to the very changes in climate that are acutely harming food production worldwide. For example, synthetic fertilizer application and livestock production together are responsible for up to 70% of emissions of nitrous oxide, a greenhouse gas almost 300 times more potent than carbon dioxide.

Thankfully, nature offers a solution that is of increasing interest to scientists. This solution—crop-fertilizing soil microbes—could help to break the cycle of synthetic fertilizer use and its attendant environmental impacts and usher in more sustainable food production systems.

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Tracing the Evolution of Beneficial Microbes

When plants first appeared on land roughly 460 million years ago, the intrepid explorers developed new strategies to source the critical nutrients required for life from the terrestrial environment.

One solution developed by these plants involved beneficial relationships with soil-borne arbuscular mycorrhizal fungi. Ancient plants were rootless, but the connection established with these filamentous fungi allowed them to access water and vital nutrients such as nitrates, phosphates, and micronutrients from the soil. In return, plants provided the fungi with energy harvested through photosynthesis that was otherwise unavailable to these microbes. The fungi continued to provide the same benefits to root-bearing plants once they evolved.

Later, about 100 million years ago, some plants, including beans, peas, and lentils—what we know as the legume family—used the same blueprint and developed a similar symbiotic relationship with certain types of soil bacteria. Known as rhizobia, these bacteria would infect the roots of legume plants and then use an enzyme to break down and fix abundant atmospheric nitrogen into accessible nutrients for the plant, supporting its continuous growth.

The synthetic fertilizer supply chain is contributing to the very changes in climate that are acutely harming food production worldwide.

Scientists addressing challenges threatening global food systems today hope that by retracing past plants' evolutionary steps, they can leverage these natural processes to reduce costly overreliance on inorganic fertilizers and support more sustainable production of the world's staple crops.

A major area of advancement includes research into plant perception mechanisms for mycorrhizal fungi and rhizobia, which has allowed scientists to make strides in understanding how legumes "decide" to engage with these beneficial organisms. For example, we now know the molecular mechanisms—involving various signals, genes, and proteins—that integrate plant nutrient status and symbiotic "willingness." Typically, legumes and other plants will "turn off" their ability to connect symbiotically with beneficial microbes once sufficient nutrients, usually supplied by fertilizers, are present in the soil.

Using knowledge from such research, along with gene editing technologies, scientists can now control and adjust the positive and negative signals in plants (e.g., legumes, rice, barley) that determine their interaction with beneficial microbes. This means that scientists can reactivate or augment plants' biological ability to source nutrients naturally from their environment, potentially reducing the existing dependence on applied fertilizers.

The Potential of Plant-Microbe Symbiosis

Although new insights hold promise, this research is still in its early stages, and much remains to be done before plants' beneficial associations with microbes can be fully utilized in the field. For instance, scientists are

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field–testing crop lines with plants that continuously engage with symbiotic mycorrhizal fungi to investigate the impact of this symbiotic connection on nutrient absorption and yield in agricultural settings.

Decades of plant breeding have traditionally been thought to have caused modern staple crops, such as maize, wheat, and others, to become more reliant on fertilizers, diminishing the role of ancient fungal symbioses. However, recent research has shown that modern varieties remain responsive to and continue to benefit from fungal symbiosis.

As scientists look to reestablish symbiotic connections in crop species, they must identify varieties with the greatest capacity to associate with beneficial soil fungi and bacteria. In parallel, more work is needed to better understand how to optimize the signaling processes that determine whether plants engage with microbes to ensure that they take full advantage of the potential of such interactions.

Ultimately, if both of these research tracks deliver promising results, scientists may be able to produce new crop varieties that significantly improve on the abilities of current varieties to benefit from interactions with symbiotic fungi. Such improved varieties, in turn, would support sustainability through higher yields and reduced usage of fertilizers.

*Nodules formed by rhizobia are seen here on the root of a young barrelclover (*Medicago truncatula*). Credit: Ninjatacoshell/Wikimedia Commons, CC BY-SA 3.0 (bit.ly/ccbysa3-0)*

The Future of Sustainable Farming

Sustainable transitions in global food systems that help farmers, particularly those without access to the latest agricultural technologies, prepare for and adapt to the impacts of climate change are badly needed. And the world cannot wait much longer for these innovations.

The global carbon emissions budget (the maximum amount of emissions that can be produced before average global temperatures rise beyond the target set by the 2015 Paris Agreement) is increasingly limited, and the likelihood of keeping global heating below 1.5°C is growing ever slimmer.

Research into optimizing plants' engagement with beneficial fungi is thus emerging at an opportune time. Compared with traditional techniques of plant breeding, genetic editing approaches like those used in this research are significantly faster and should cut the time needed to deliver new crop varieties that meet imminent climatic challenges.

Sustainable transitions in global food systems that help farmers prepare for and adapt to the impacts of climate change are badly needed.

Enhancing symbiotic relations with arbuscular mycorrhizal fungi and rhizobia will not only allow crops to deliver high yields with less fertilizer but will also offer other broad sustainability benefits for agricultural production. For instance, beneficial fungi can support the sequestration of more atmospheric carbon underground while at the same time significantly augmenting soil fertility.

Applying knowledge gained from research into the roles of beneficial fungi and bacteria will likely be foundational in achieving the goal of the United Arab Emirates Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action, signed in December at the COP28 climate talks in Dubai. The declaration saw more than 150 countries commit, for the first time, to transitioning to sustainable and resilient food systems as a key pillar of climate action.

Already, farmers, scientists, and businesses have taken important steps toward establishing more sustainable farming practices for the world's major staple crops. For instance, rice farming (which is responsible for roughly 10% of global methane emissions), along with maize and legume farming are embracing climate-smart practices. These practices include the adoption of improved tillage and pest management practices as well as cultivation techniques that reduce greenhouse gas emissions, water consumption, and the time needed to grow the crop. Recent research suggests that rice production, like that of many other staple cereal crops, also has extensive potential to benefit from enhanced arbuscular mycorrhizal symbiosis.

Scientists are continuing to build a clearer picture of the processes that dictate engagement with beneficial microbes and how we can influence these processes for good. Although this research remains in its early days, the potential to optimize crop biology for better nutrient uptake is a promising, yet underappreciated, solution for reducing fertilizer dependence, promoting sustainable food production, and improving food security for communities around the world.

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Geoscience Departments can "Phone a Friend" for Support

By Anne E. Egger and Walt Robinson

The Traveling Workshops Program provides customized assistance and expert facilitation to support geoscience groups as they adapt to shifting student and institutional interests.

Faculty from Pitzer College and Pomona College, both in Claremont, Calif., participate in an activity to define program learning outcomes during a 2019 workshop led by the Traveling Workshops Program (TWP). Credit: Deborah Gross

Geoscientists know well the value of their work and their discipline. Innovative geoscience research and education are critical to addressing the major societal challenges we face today, from sustainably producing sufficient energy and resources to building communities resilient to natural hazards to adapting to and mitigating the effects of climate change [*Summa et al.*, 2017; *Tewksbury et al.*, 2013]. And geoscientists bring to these challenges a unique set of tools, including methods for testing hypotheses against Earth observations, capabilities for spatial and temporal reasoning across scales, and systems thinking that recognizes interconnections among Earth system processes [*Manduca and Kastens*, 2012].

Unfortunately, the value of geoscience is not always as obvious to others. Because it is often absent from high school curricula, many people discover the discipline for the first time in college [*Levine et al.*, 2007; *Stokes et al.*, 2015]. Departments work hard to attract students through introductory courses that focus on popular subjects such as volcanoes and earthquakes, dinosaurs, and what makes our planet habitable. Still, geoscience departments are typically smaller than other science departments.

Twenty years ago, Lisa Rossbacher and Dallas Rhodes described a tension on college campuses between groups of departments considered essential (such as English, math, biology, and history) and those whose existence requires continual justification. Rossbacher and Rhodes, both geologists themselves, put geoscience departments in the second category because they are relatively small, expensive to run (think of the high costs of field trips, equipment, and sample storage space), and sometimes wade into topics that turn out to be controversial in the public eye (e.g., climate change, hydrofracking, and water quality).

Long-standing links between geoscience programs and the extractive industries that have traditionally hired a number of their graduates—also influence perceptions of the discipline. These links can cause large swings in the number of students interested in taking introductory courses and pursuing geoscience degrees, as seen in the 1980s and again in recent years [*Keane*, 2022].

The geosciences have evolved substantially in the past 20 years, fueled by technological advances, interdisciplinary approaches, and a rapidly changing planet. But a perception that geoscience programs are nonessential to universities remains. As a discipline, geoscience also continues to struggle to attract and retain a diverse range of students and to overcome an emphasis on ableism and a history of exclusion. These issues pose challenges to geoscience departments, programs, and courses (both undergraduate and graduate), leaving them vulnerable to restructuring or elimination—especially as many universities face declining enrollments and shrinking budgets—and creating pressure to rebrand to attract more students.

But it does not have to be this way. Departments are far better positioned to adapt to and thrive in changing academic climates if they know their value, and communicate it within and beyond their respective campuses; have well-designed courses and curricula that support their students' interests, growth, and success; and have a clear vision of what they do well and how they can improve.

Such departments provide models of success for others in their institutions and in the discipline. Achieving these aspirations, however, often requires examining deeply entrenched habits and implicit biases and building a common vision and a will to act. Those processes can be difficult even when time is set aside for them. So where can departments turn for help?

Since 2014, the National Association of Geoscience Teachers' (NAGT) Traveling Workshops Program (TWP) has run workshops for more than 80 departments and programs at higher education institutions in 33 U.S. states (and one other country) to support them in building stronger and more inclusive cultures, curricula, and courses (Figure 1). The TWP, one component of NAGT's long-running professional development programming, relies on educators with diverse expertise and experience to facilitate a highly customized process that better enables participants to navigate change.

> The geosciences have evolved substantially in the past 20 years, but a perception that geoscience programs are nonessential to universities remains.

As leaders of the TWP and facilitators ourselves, we find supporting individuals and departments in this way to be fulfilling and rewarding. More important, however, we have seen that the TWP works—participants leave the workshops energized and motivated, with clear and achievable plans for strengthening their programs.

Building Potential for Successful Change

The impetus for change and the need for support within departments can stem from a variety of sources. In our experience, we have seen interest in the TWP come from the following sources:

- programs needing to restructure after several faculty retired and/or new faculty arrived
- programs facing shifts in student interest from traditional geology topics to environmental geoscience and sustainability
- departments being pressured to increase course enrollments and numbers of majors
- a system of community colleges wanting to improve the quality and student appeal of their geoscience instruction
- a cross-departmental environmental sciences program seeking to demonstrate its value to students, parents, faculty, and its institution

Anyone from a department, program, or institution can request assistance from the TWP by providing information about their group and what they hope to accomplish. The applicant need not have a formal leadership role, although their department chair (or other relevant leader) must play a role in the process. Indeed, a program leader's commitment to support—and to colead—change efforts is critical to success [e.g., *Graham*, 2012].

The TWP management team matches facilitators to a request on the basis of availability and relevant expertise and experience. Facilitators are themselves geoscience or environmental science faculty who have been brought into the program because of their wide-ranging experience in successfully navigating changes in their own institutions and supporting others in their planning.

The matched facilitators, who work in pairs, meet with the applicant and department leader to begin planning the workshop, which typically takes place over 2 days. They use a backward design approach [*Wiggins and McTighe*, 2005], first defining desired outcomes and learning about the department's culture and history before determining what steps are needed for the program to achieve those outcomes.

In these initial discussions, facilitators also learn more about the broader institutional forces at play. They typically meet with a dean, provost, or other leader to better understand the administration's perspective on the department, how it is perceived within the college or university, how its challenges fit into the bigger picture of the institution, and what the hopes are for change. In our experience, these conversations are highly productive and positive: Deans and provosts want their departments to thrive and encourage outside facilitation—frequently even footing the bill ($5,000 plus travel for the facilitators) for the workshop.

These planning conversations help the facilitators develop a customized workshop agenda that meets the needs of the department or program through engagement in time-tested activities. Examples of activities that TWP leaders have developed include an analysis of strengths, weaknesses, opportunities, and threats (SWOT), a process for developing course- and program-level learning outcomes that begins with envisioning a successful student, and a reflection about identity and implicit bias that leads to developing strategies for attracting and supporting all students.

How the Workshops Work

A key focus of the TWP is bringing everyone in a department or program together to develop a shared vision and goals from which actions can emerge. This critical level of engagement is why we travel to bring the workshop to the program in need. (Most workshops happen in person, although we also offer virtual programming for dispersed groups.) Having departmental representatives attend an off-site workshop and then report back to their larger group does not achieve the same result, primarily because there is no opportunity to build a common vision, which can leave many uninvested in the process.

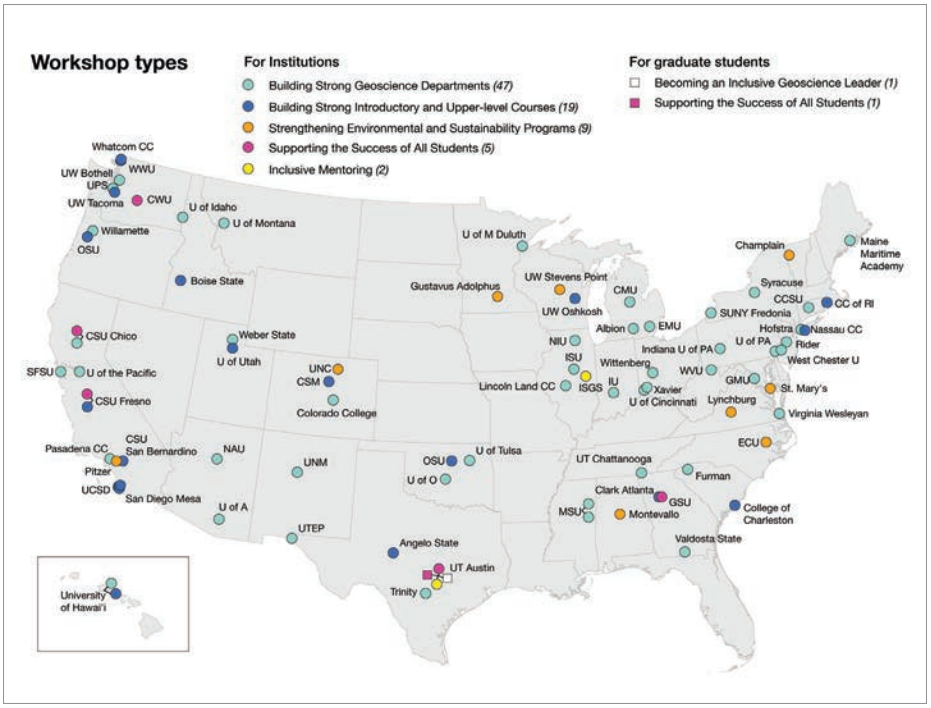


Fig. 1. The TWP has facilitated workshops for more than 80 departments and programs since 2014. Institutions where multiple workshops were held are connected by lines, and the numbers of each type of workshop are shown in the legend. Alaska is not shown because no workshops have been held there. A Building Strong Geoscience Departments workshop held at the Universidad Técnica Particular de Loja in Ecuador is also not shown.

Facilitators help participants clarify and prioritize concrete steps that most effectively contribute to the group's desired outcomes.

In addition, the needed conversations can be difficult and fraught, surfacing deeply entrenched feelings and power dynamics. It is common for department chairs to tell us ahead of time of distinct groups in their departments who do not see eye to eye. Or sometimes we learn that newer faculty don't contribute in faculty meetings or are talked over by longer-tenured colleagues. These dynamics are why we facilitate workshops: We provide objective leaders who ensure that everyone is heard and that discussion remains collegial and productive.

To lay the groundwork for a productive workshop, participants complete "homework" in advance so they are prepared for the discussions ahead and so that during the workshop, they can focus on the group interaction.

For workshops focused on strengthening departments overall, the homework might entail exploring demographic data about their institution and program, revisiting their program's mission and goals, and reflecting on the impacts they want to have on students.

We often ask individuals to complete a self-assessment about their department that is designed around established characteristics of a thriving department. With these results, we can highlight where there is agreement and disagreement and use those insights as starting points for discussion.

For workshops focused on course design, we also ask participants to reflect on demographic data about their students, the learning outcomes of their courses, and how their courses fit into the curriculum.

Workshop activities are interactive and discussion rich, and we apply many of the same strategies we use in our own teaching to ensure that all participants have the opportunity to contribute.

Specifically, we create small groups to work on and report out on tasks; we ask everyone to reflect on activities, write down their thoughts, and then share them; and we limit individual contributions so that people who are more talkative don't dominate conversations. In one case in which we knew a department was feeling collectively pessimistic, we held up an image of a downward spiral when the conversation was going in a negative direction. Gently calling out nonproductive discussion allowed us to get back on track.

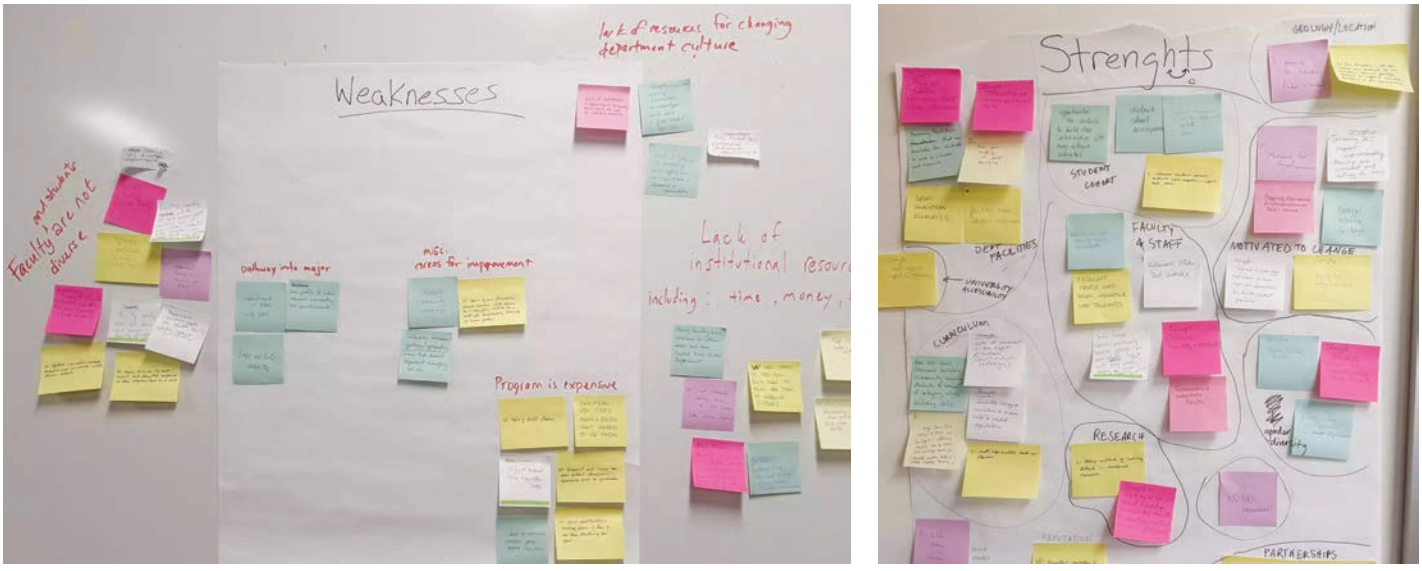
Following the first day of discussions, participants complete a "road check"—an anonymous three-question evaluation that allows facilitators to get a sense of how participants feel the workshop is going, respond to concerns, and adjust the plan for the next day if needed.

Regardless of the workshop theme, a major focus of the second day is on action planning: The facilitators help participants clarify and prioritize concrete steps that will most effectively contribute to the group's desired outcomes—and decide who will take them. Examples of such actions include updating a department's website and social media presence to increase program visibility; creating or restructuring an advisory board to better represent current job opportunities and priorities; and submitting a proposal for new program learning outcomes and a major curriculum to an institution's curriculum committee.

Measures of Success

At the end of the scheduled agenda, participants complete an end-of-workshop evaluation that asks respondents to rate aspects of the workshop and their overall satisfaction and to answer open-ended questions that allow for more explanation. The feedback we have received from more than 500 of these evaluations has been overwhelmingly positive (an average overall satisfaction rate of 8.9 out of 10), with comments often focusing on the benefits of the facilitation and how it enabled input from everyone involved.

One participant commented, "Having attempted to steer strategic planning discussions and action planning in our department for a while, it was tremendously helpful to have skilled facilitators, knowledgeable about the issues we are facing, to guide us."



The TWP has developed a variety of customizable workshop activities that can be tailored to meet the needs of a specific department or program. One example is a SWOT analysis activity in which participants identify strengths, weaknesses, opportunities, and threats relevant to their program's desired outcomes. Credit: Anne E. Egger

Another said, "The workshop provided the (very) necessary space for my [department] to focus on future hires, curriculum change, and relevance within our institution. All of the [department] faculty were able to agree on specific goals and actions related to these themes… which definitely feels like progress."

Unfortunately, we do not have a formalized way to track long-term outcomes of individual workshops, nor can we directly compare the efficacy of the TWP with other interventions (our knowledge of higher education and discipline-specific professional development suggests that these comparisons are hard to come by). However, informal follow-ups and other kinds of feedback from participating programs have provided additional confirmation of the program's efficacy.

A number of programs have requested multiple workshops, sometimes the same type of workshop after several years have passed, sometimes a different type (Figure 1). In such requests, applicants typically mention how valuable the first workshop was to their department or program and that they knew where to turn for additional support.

When opportunities arise, we also check in informally with departments (perhaps connecting with a department chair at a meeting) to learn how they are doing in implementing their action plans. Almost universally, the institutional landscape has continued to change, but they frequently report being better equipped to navigate and respond to that change because of the work their members did together in the workshop and that building a shared vision was key to their success.

Adapting to Meet Needs

Facilitators also share their own reflections on workshops with the TWP leadership team, focusing on what worked well, what didn't quite go as planned, and what could be improved to better support the group they worked with. By analyzing the participant evaluations and facilitator reflections together, we can identify common themes and make changes as needed, creating a process of continuous improvement in the TWP.

As a result, our offerings evolve, much as departments and programs must, with changes in scientific disciplines, student demographics and interests, and institutional contexts. We are also responsive to community members' input about the challenges they are facing and requests for support.

The TWP's initial efforts were focused on strengthening departments and teaching, and these two themes underlie the most common workshops we've offered (Figure 1). Starting in 2017, with funding from the Interdisciplinary Teaching about Earth for a Sustainable Future (InTeGrate) project, we developed two new themes. One broadened the focus from a single department to building strong cross-campus environmental and sustainability programs and another focused on department culture and inclusivity and supporting the success of all students. At the same time, we refined and added to the two main themes to expand their relevance beyond traditional geoscience courses and programs.

More recently still, we developed two more workshops—both representing new directions and approaches—in response to community requests. In 2020, we received a request to offer programming for graduate students, with the idea of supporting future faculty in developing transferable skills. That request resulted in the development of TWP's Building Inclusive Geoscience Leaders workshop, designed specifically for students (Figure 1).

Then in 2023, we were asked to develop a workshop focused on inclusive mentoring. Unlike most of our workshops, which benefit from being offered in person, the Inclusive Mentoring workshop works very well as a virtual offering, allowing us to bring together mentors who may all be involved in a single program but are widely dispersed physically. The virtual offering also allows time between sessions for participants to enact and get feedback on some of the strategies we discuss.

By analyzing the participant evaluations and facilitator reflections together, we can identify common themes and make changes as needed, creating a process of continuous improvement.

In May 2024, we expanded beyond our typical audience base at academic institutions to offer this new mentoring workshop for a state geological survey that is hosting several summer interns and sought additional support for their scientists.

As we look to the future, the TWP will continue to work with programs to address common challenges and build skills. Given our recent positive experiences with new workshop themes and repeat customers, we also plan to promote these options more specifically and add more opportunities for graduate students and postdocs. We encourage anyone interested to reach out to discuss how we can provide support.

By continuing to facilitate difficult discussions about needed changes and how to achieve them, NAGT's traveling workshops are helping the geoscience community adapt to changing academic and workforce climates, giving departments and programs the tools they need to demonstrate their value and provide welcoming experiences for all students.

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What Happens in the Troposphere Doesn't Stay in the Troposphere

Commercial flights, like this one over Greenland, often fly through the lowermost stratosphere, an isolated portion of the atmosphere that is being directly affected by surface ozone pollution. Credit: M. J. Prather

In the final decades of the 20th century, stratospheric ozone depletion—often called, not quite accurately, the ozone hole—was a widespread concern. Halocarbons, including chlorofluorocarbons used as coolants in refrigerators and propellants in aerosol spray cans, were linked, beginning in the mid-1970s, to the problem. However, global efforts to reduce halocarbon use have since led to a slow but steady recovery of the stratospheric ozone layer.

About 90% of Earth's ozone is in the stratosphere, where it protects humans, plants, and animals from the Sun's most damaging ultraviolet rays. Ozone is also a highly reactive gas and the 10% of it that is in the troposphere—the atmospheric layer between Earth's surface and the stratosphere—can be damaging to human health and the environment. Tropospheric ozone is the primary component of smog, for example, and its concentration has been increasing globally over the past hundred years.

Ozone molecules form in the lower atmosphere when pollutants—such as volatile organic compounds and nitrogen oxides—chemically react in sunlight.

But, as *Prather* writes in a new paper, "what happens in the troposphere doesn't stay in the troposphere." Some of these molecules travel up into the stratosphere when the two atmospheric layers exchange air. The author suggests that this upward migration of ozone may make it difficult to assess the recovery rate of the depleted stratospheric ozone layer accurately and may also affect how researchers interpret the results of a worldwide reduction in halocarbon use.

Using a chemistry transport model, the author examined spillover rates of ozone moving from the troposphere into the stratosphere. He found that about 20% of the observed stratospheric ozone recovery may be attributable to increasing levels of tropospheric ozone.

Although this ozone transfer has been accounted for in whole-atmosphere model predictions of ozone trends, the author suggests that its role is larger than scientists have accounted for in assessments of stratospheric ozone recovery and that future studies of ozone depletion should be adjusted accordingly. A global reduction in air pollution would reduce tropospheric ozone levels and improve air quality—but it would also reduce stratospheric ozone. (*AGU Advances*, https://doi.org/10.1029/2023AV001154, 2024) **—Rebecca Owen,** *Science Writer*

Expecting the Unexpected Could Help Us Prepare for Climate Extremes

Western North America experienced an unprecedented heat wave in summer 2021, with many locations in the region breaking all-time maximum temperature records by more than 9°F (5°C). Although weather models forecasted the warmer-than-average conditions that summer, the extreme temperatures caught the climate science community by surprise. In the past year, so have other catastrophic, climate events such as floods in Libya and China and record-breaking wildfires in Canada.

Our collective unpreparedness for such extreme climate events should be a cause for concern, argue *Sherwood et al.* The authors contend that a reliance on models that don't account for enough relevant factors and a tendency toward linear thinking have narrowed perceptions of climate change risks.

Central to their argument is the idea that society is too focused on the expected gradual consequences of climate change and not enough on high-impact, low-likelihood occurrences and tipping points—regime shifts in which systems can change rapidly and irreversibly. The authors suggest that as a result, we are overlooking critical potentialities in our efforts to adapt to and weigh mitigation options for a warmer future.

Unprecedented heat waves may serve as a harbinger of future climate. Credit: m01229/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

The authors outline two questions for climate scientists to consider. First, what are the high-impact, low-likelihood hazards and irreversible changes that society should worry about, and how can their risks be measured and communicated? Second, how can scientists identify achievable and safe pathways to a future climate that also meet human needs?

To answer these questions, climate scientists must consider a broader array of risks than they conventionally have, examining how these risks affect not just the climate but also society and the larger biosphere. This effort will likely involve working across disciplines and using new modeling approaches that better represent tipping points, low-likelihood events, and other aspects of physical and human systems compared with current approaches.

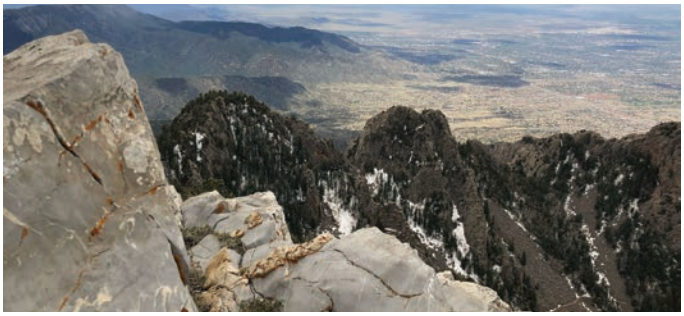
The authors also emphasize that clear communication will be crucial in conveying climate risks to the public and coordinating across scientific disciplines. (*Earth's Future*, https://doi.org/10.1029/2023EF004297, 2024)

—Aaron Sidder, *Science Writer*

How Tiny Cracks Lead to Large-Scale Faults

The geological and topographical features that make up the world we live in are shaped in large part by faults and fractures in Earth's brittle crust. Faults arise from preexisting microscopic imperfections within rock. When the rock is subjected to increasing stress, tiny cracks form at these imperfections. The cracks grow and interact until the rock suffers larger-scale damage.

Computer simulations of this process can deepen our understanding of faulting and the long-term tectonic shaping and reshaping of Earth's surface. However, it is challenging to adequately capture the evolution of rock damage in a computationally efficient way.



Researchers developed a model of how tiny cracks in rock (such as those seen in the foreground) can lead to faults that reshape Earth's surface, as in the Sandia Mountains of New Mexico (seen here). Credit: Jean-Arthur Olive

Petit et al. address this challenge by introducing a new set of equations that describe how rocks deform within Earth's crust. With this approach, called the subcritically altered Maxwell (SCAM) framework, they aim to capture microscale processes of rock damage and link them to larger-scale deformation in a way that is straightforward enough to be widely used by researchers studying Earth's crust.

What sets the SCAM framework apart from prior approaches is that its parameters can be calibrated against data from rock deformation experiments, but at a low computational cost. This allows for more accurate simulation of how microscopic cracks accumulate and interact to form faults. The researchers also demonstrate that the SCAM framework can be used to simulate millions of years of changes in a 10-kilometer-thick brittle crust. The fault sizes and displacements in the simulation mirror real-world data, highlighting the framework's potential value.

The SCAM framework has certain limitations, some of which could be addressed through future refinement. Still, as is, it could help deepen understanding of phenomena such as earthquake hazards, rock weathering and erosion, the permeability and flow of fluids within rock, and the long-term fate of tectonic plates. (*Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2023GC011229, 2024)

—Sarah Stanley, *Science Writer*

Seals Help Scientists Make Discoveries in Antarctica's Bellingshausen Sea

Ice shelves surrounding Antarctica have been melting with increasing speed in recent years. Much of this melting happens from below, as warm water eats away at their bases.

This warm water is moved around Antarctica by currents that remain only partially understood because of the continent's vastness and remoteness. Mapping these currents in better detail will improve understanding of the future of the continent's mantle of ice.

The 2013 Marine Mammals Exploring the Oceans Pole to Pole (MEOP) database relied on seals to carry temperature and salinity sensors into remote regions of West Antarctica's Bellingshausen Sea. *Flexas et al.* combined data from this initiative with 2020 data from an autonomous undersea glider to take a better look at the hydrographic properties of the region, including temperature, salinity, and dissolved oxygen levels.

They learned that meltwater flowing out of the Bellingshausen Sea—a relatively understudied body of water west of the Antarctic Peninsula—has a strong effect on ice shelves throughout West Antarctica. They also uncovered a seafloor trough they named Seal Trough for the instrument-laden pinnipeds that helped discover it.

The researchers found two distinct sources of meltwater moving through the sea, one from the Venable Ice Shelf flowing through Belgica Trough and the other from the Abbot Ice Shelf farther west flowing through Seal Trough. Both flows contribute to the Antarctic Coastal Current (AACC) and may also affect ice shelves in other regions of Antarctica. Data also indicated that both the Bellingshausen Sea and the AACC extend farther west than previously realized, with the sea extending to Seal Trough and the AACC reaching into the Amundsen Sea.

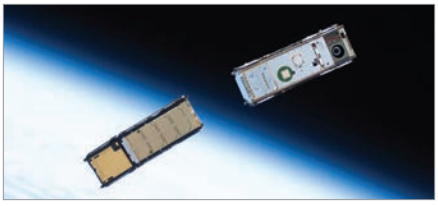
Researchers used data gathered by an autonomous glider and instrumented seals to learn more about Antarctic currents. Credit: Etienne Pauthenet (IRD)

Future work should more deeply probe the contributions of ice shelf water to the Bellingshausen Sea, the authors say, and should be updated with synchronous data on water flows, given the 7-year disparity between their current data sets. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2023JC020080, 2024) **—Nathaniel Scharping,** *Science Writer*

Tiny Satellites Can Provide Significant Information About Space

CubeSats are satellites constructed of individual cubic units. Each unit is a bit smaller than a square tissue box, about 10 centimeters (4 inches) on each side. Initially developed 2 decades ago as an inexpensive platform for students to learn about satellite development, CubeSats weren't initially thought of as devices for collecting valuable data.

However, these tiny satellites can capture high-quality information and measurements that make them useful for students and scientists alike.



Two CubeSats orbit Earth. Credit: NASA

Li describes two student-led research projects that used CubeSats to collect data about the near-Earth space environment.

The Colorado Student Space Weather Experiment (CSSWE), began in 2010 as a University of Colorado Boulder graduate course. Its focus was on designing and building a CubeSat and an accompanying ground station to measure the flux of solar protons and Earth's radiation belt electrons. Students kept detailed documentation to ensure the project's continuity as their peers completed the course, and their satellite, equipped with an electron and proton telescope launched on 13 September 2012 as a secondary payload. Their ground station in Boulder received information from it as it first passed overhead. Graduate students were responsible for continued mission operations, eventually developing an automated operation system.

The CSSWE affected the academic and professional careers of more than 65 students—their research with the CubeSat contributed to numerous dissertations, peer-reviewed papers, and even scientific breakthroughs: The data gathered from the CSSWE helped resolve a long-standing mystery about the source and behavior of energetic electrons in Earth's radiation belts.

The second CubeSat project built upon this knowledge. With a bigger budget and continued student interest, the Colorado Inner Radiation Belt Experiment (CIRBE) team developed another 3U CubeSat, this one more advanced than its predecessor, to gather more information about radiation belt electron dynamics and behavior. The CIRBE was launched in April 2023 and has been providing data ever since.

Both projects have contributed to the research and understanding of the near-Earth space environment and may offer valuable insights into how to conduct high-quality space research at a low cost. (*AGU Advances*, https://doi.org/10.1029/2024AV001256, 2024) **—Rebecca Owen,** *Science Writer*

Convergence Science in the Arctic

The Arctic is undergoing rapid changes that affect its natural environment, its people, and its role in global-scale natural processes. The interplay of climate change, industrialization, and other stressors makes the Arctic an intriguing subject for convergence science—an approach characterized by communication and integration across disciplines to address specifically defined problems.

The aim of convergence science is to generate new paradigms and ways of viewing problems that reach beyond any single discipline. Despite the rising popularity of this concept over the past decade, few publications have addressed the specifics of how to put it into practice—and none has focused on the Arctic.

A Nenets reindeer team stands near the Yamal tundra's industrial railway in northwestern Siberia, Russia, in summer 2023. Credit: Alexandra Terekhina

A new paper by *Ivanov et al.* aims to do just that. In 2020, a team of Earth system scientists, ecologists, anthropologists, and engineers, representing a range of countries and cultural identities, organized a series of workshops to explore how to apply convergence science to the changing Arctic. In particular, they focused on how climate change and industrialization are driving change in the Yamal Peninsula.

Located in northwestern Siberia, the Yamal Peninsula of Russia extends more than 700 kilometers north into the Arctic Ocean. It is home to Indigenous Nenets residents living in small villages or leading nomadic lifestyles as fishers and reindeer herders. It also holds vast natural gas reserves, leading to the development of industrial infrastructure and new towns over the past 50 years.

Workshop participants started out in their disciplinary comfort zones and then gradually integrated disciplines by identifying links between different natural, social, and industrial elements of the Yamal Peninsula.

This approach enabled the participants to develop a shared language, ultimately leading to the formulation of several top-level science questions, such as "How do warmer winters and seasonal shifts transform human and reindeer lives in the tundra?" Additional questions emerged from each top-level question, such as "How does human activity modify top-down control of trophic interactions in tundra food webs?"

As the climate warms, the terrestrial tundra food web of Yamal has transformed. The red fox (right), seen here near a research station in Erkuta in southern Yamal, is increasingly invading the domain of the Arctic fox (left). Credit: Aleksandr Sokolov

In addition to sparking new research questions, this paper could serve as a blueprint for how to apply convergence science to studying Arctic change. (*Earth's Future*, https://doi.org/10.1029/2023EF004157, 2024) **—Sarah Stanley,** *Science Writer*

How Mantle Movements Shape Earth's Surface

The movement of tectonic plates shapes the rocky features of Earth's surface. Plates' convergence can form mountain ranges and ocean trenches, and their divergence can form oceanic ridges. But it's not just the plates that influence Earth's topography. The mantle layer underneath exerts its own subtle influence, referred to as residual topography, which can be seen even in places located far from tectonic plate edges.

To better understand how the mantle affects topography, *Stephenson et al.*, building on previous work focused on the oceans, created two new databases. One compiles 26,725 measurements of crust thickness around the globe, the largest such database to date, along with estimates of regions seismic velocities. The other contains data from laboratory analysis of seismic velocity as a function of temperature, density, and pressure. Together these measurements helped disentangle crustal influences on topography from mantle influences to identify residual topography.

The researchers found that differences in the temperature and chemical structure of the mantle can cause swells and basins in the landscape distinct from those that form at the edges of tectonic plates. These features can rise or fall by up to 2 kilometers and stretch for hundreds to thousands of kilometers—all within the interiors of plates.

Some of the highest swells (about 2 kilometers), which are thought to correspond to locations where the mantle is particularly hot, can be found in the Afar–Yemen–Red Sea region, western North America, and Iceland. Some of the deepest basins (deeper than about 1.5 kilometers), where the underlying mantle is thought to be cooler, are in areas near the Black, Caspian, and Aral seas, as well as in the East European Plain. This pattern of swells and basins may control—to some extent—where significant erosion and sedimentary deposition occur.

These topographical features can develop slowly over millions of years, but they nonetheless control important geological processes. According to the researchers, these findings could help explain the existence of magmatism found far from plate boundaries. They also could help scientists understand the elusive effects of mantle flow on Earth's on the surface through geologic time. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2023JB026735, 2024) **—Rachel Fritts,** *Science Writer*

Dear *Eos*,

Mysteries abound regarding groundwater composition, inventories, and fluxes. This is particularly true for the age of groundwater venting from submarine and sublacustrine vents such as the submerged karst sinkholes in the Laurentian Great Lakes. Currently, we have no idea whether the groundwater venting from nearshore and offshore sinkholes in Lake Huron is days, years, centuries, or even millennia old—even though this know-how is key to understanding aquifer recharge and turnover, assessing its contribution to lake levels, and determining the potential for groundwater contamination and its transfer to the lake's interior.

Here on board NOAA's R/V *Storm*, divers have just brought up groundwater samples in airtight Van Dorn bottles from the bottom of Middle Island sinkhole (a depth of approximately 23 meters). Working in the shade of an umbrella, graduate student Cecilia Howard and research technician Tony Weinke are carefully draining the groundwater samples into copper collection tubes that will be sealed without bubbles or exposure to the atmosphere for sulfur hexafluoride (SF6) measurements. Because anthropogenic SF6 arose about 70 years ago, its presence or absence in venting groundwater will inform us whether it is relatively young or quite old, respectively.

—**Bopi Biddanda** and **Tony Weinke,** Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich.; **Cecilia Howard** and **Diana Velazquez,** Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor; and **Steve Ruberg,** Great Lakes Environmental Research Laboratory, NOAA, Ann Arbor, Mich.

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