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Eos

SCIENCE NEWS BY AGU

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Rethinking Air Quality Guidelines

Solar Farms as Biocrust Nurseries

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The Policy of Science

Science policy isn't limited to contentious political dialogue or administrative protocol. It's not *not* about those aspects of communication, but it also includes on-the-ground outreach, fresh insights on familiar issues, and nimble adaptation of existing policies.

Atmospheric scientists successfully engage all of the above approaches in "Setting the Stage for Climate Action Under the Montreal Protocol." On page 30, Stephen O. Andersen, Marco Gonzalez, and Nancy J. Sherman outline how a dozen academic papers informed the Kigali Amendment, which expanded the Montreal Protocol from a treaty focused on protecting Earth's ozone layer to one adapted to address the drawdown of hydrofluorocarbons and encourage greater energy efficiency.

In its 150-year history, the World Meteorological Organization (WMO) has also adapted—to shifts in geopolitical balance, wars both hot and cold, and new technologies from air, land, and sea. WMO's most conspicuous contemporary challenge, however, is neither digital nor diplomatic: It's the private sector. "WMO Weathered the Cold War, but Can It Survive Capitalism?" asks Bill Morris on page 22.

To more effectively address such discourses around data, discovery, and solutions science, the scientific community needs policies to better recruit and retain a broad network of members. These policies can build foundations in undergraduate education, as Melissa A. Burt, Rebecca T. Barnes, Sarah Schanz, Sandra Clinton, and Emily V. Fischer outline in "Mentorship Builds Inclusivity and Belonging in the Geosciences" on page 36.

We hope this cross section of science policy stories—both international and intersectional—illustrates how scientists are informing and influencing the world around them.

Caryl-Sue Micalizio, Editor in Chief

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Janice Lachance, Interim Executive Director/CEO

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Building supportive, inclusive, and equitable communities spells PROGRESS.

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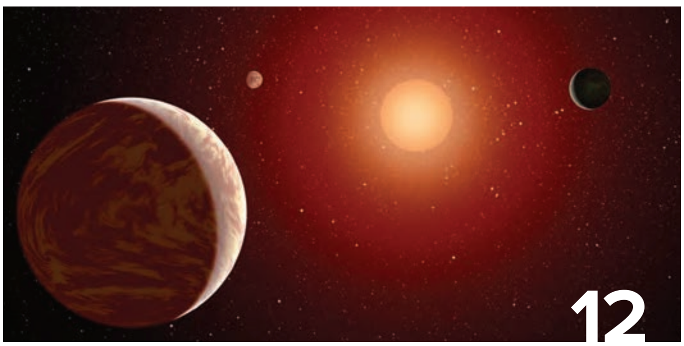

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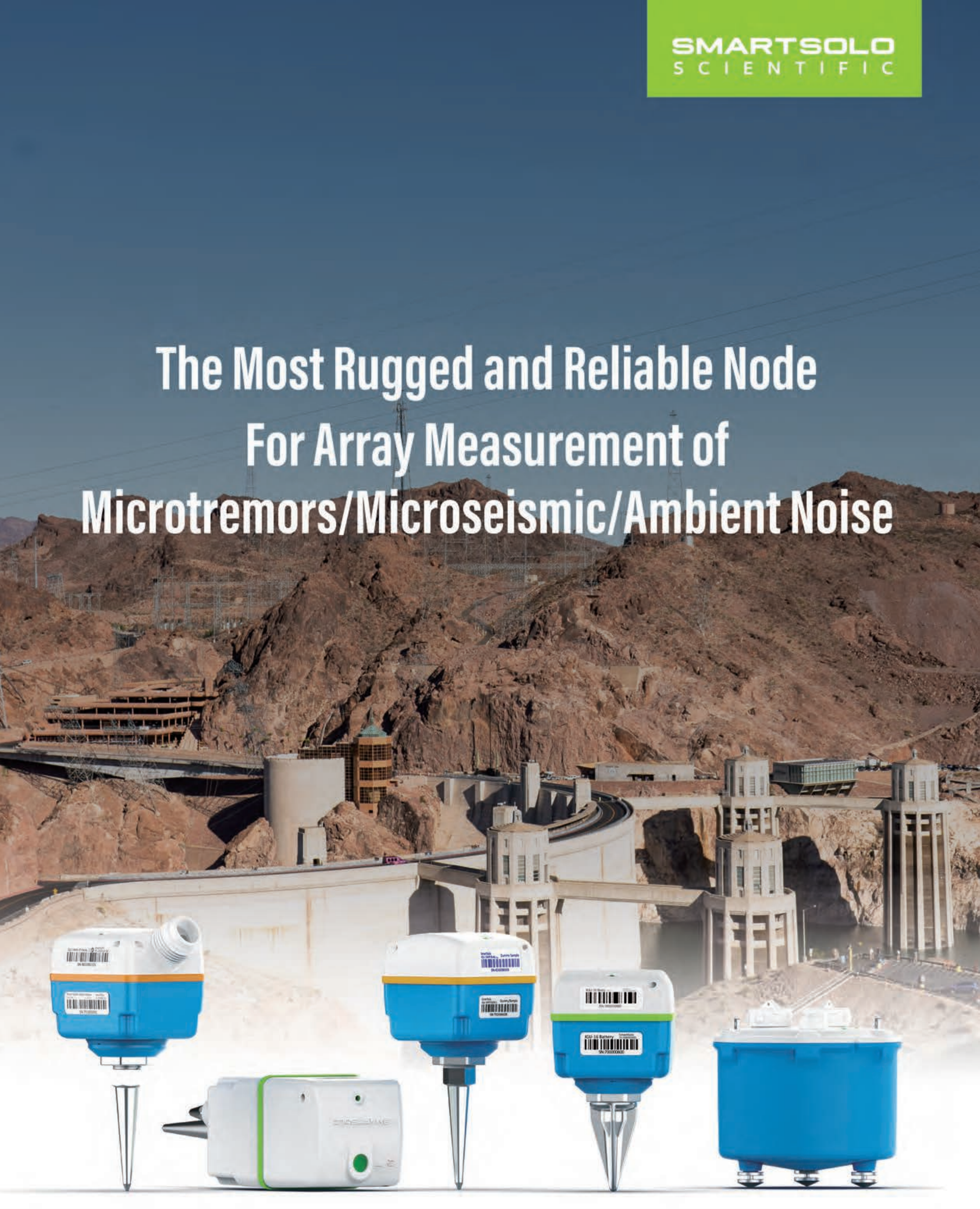

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A Mission to Uranus Could Help Find Planet 9

Uranus has a sideways orbit, unique weather patterns, and unusual rings, and its moons might have subsurface oceans. A mission to the ice giant would have a great deal of scientific potential, and now there's another compelling reason to visit: Data gathered on the way to the distant world could aid in the search for an elusive ninth planet suspected to orbit beyond Neptune.

With current technologies, positional data gathered during the mission's Jupiter-to-Uranus cruise stage could shrink the search window a thousandfold and make finding the planet with high-powered telescopes much more feasible, according to a team of doctoral students at the University of Zürich in Switzerland. Their study, which has been submitted for publication in the *Monthly Notices of the Royal Astronomical Society*, demonstrates that NASA's proposed flagship mission to Uranus could yield scientific discoveries beyond the Uranian system.

A hypothesized ninth planet, illustrated above, might lurk in the outer solar system and shape the orbits of tiny icy bodies. Credit: Caltech/R. Hurt (IPAC)

Narrowing the Search Grid

In 2016, two astronomers noticed that the orbits of several small icy objects in the outer reaches of the solar system tracked with each other too well to be random. Computer modeling and subsequent observations suggested that an unseen body far beyond Neptune might be gravitationally shepherding those objects into alignment. The astronomers dubbed the hypothesized body Planet 9 and have been trying to pinpoint its location ever since. (Not all astronomers are convinced of its existence.)

The planet, if it's out there, would be very faint, and the high-powered telescopes that could find it have narrow fields of view, better suited to pinpoint targeting than sweeping searches. Astronomers would need to know exactly where to look, explained coauthor Jozef Bucko, and as of now the search grid covers too large a swath of sky to earn highly coveted telescope time. "To persuade the observational astronomers to focus a telescope and try to search for it—this is very expensive, and we need to have strong arguments," he said.

That's where the proposed Uranus Orbiter and Probe mission comes in. During its travels to the outer solar system, it would occasionally ping a receiving station on Earth to let technicians know where it is, how fast it's going, and the status of onboard systems. This is standard procedure. Mission teams use these kinds of ranging data to keep a spacecraft on course; anything with enough gravitational influence—such as planets, asteroids, or comets—could nudge it off its path.

"If there is a gravitational anomaly in the solar system, in this case, Planet 9, the trajectory of the spacecraft would be affected," said coauthor Deniz Soyuer. The planet's gravity would subtly tug the spacecraft toward it, registering as a small change in speed or direction during the craft's 10- to 15-year cruise toward Uranus. Given the theorized mass and distance of Planet 9—6.3 Earth masses and 460 times the Earth–Sun distance—the planet, if it exists, "will definitely have a nonnegligible effect on the trajectory of a spacecraft," they said.

The idea of using spacecraft ranging data to find Planet 9 has been around for a few years, explained astronomer Mike Brown of the California Institute of Technology, one of the scientists who proposed the existence of Planet 9 in 2016. Astronomers tried using ranging data from NASA's Cassini mission to Saturn to pinpoint the planet but were left with too much of space to check.

"This paper gives a nice twist on the idea by tracking the spacecraft over a wide range of distances," said Brown, who was not involved in the study. The spacecraft would traverse more than 2 billion kilometers (1.2 billion miles) between Jupiter and Uranus. "One bit of good news is that the greater the distance [from Earth], the greater the effect of Planet 9, so making it all the way out to Uranus gives you quite a bit of leverage," he said.

The researchers calculated that if a Uranus mission uses Cassini-era technology, data from its cruise phase could narrow the search grid to 0.2 square degree. It's still a large swath of the sky, the team said, but a thousandfold improvement over the search range possible with Cassini data.

It's a thousandfold improvement over the search range possible with Cassini data.

If more modern technology can reduce the noise level of the ranging data, the search grid could shrink another 20 times smaller, the team said. "You don't really need that much of an improvement to be able to localize [Planet 9] to a place where you can convince people to point their telescopes at it," Soyuer said. This research was presented at the European Geosciences Union General Assembly 2023.

> **"I think it is great that people are thinking creatively about different ways in which we could eventually track down this elusive planet on the edge of the solar system."**

Creative Solutions

A large uncertainty in how precisely ranging data could locate Planet 9 is not found with technology on board the spacecraft, explained coauthor Lorenz Zwick, but, rather, with limitations back on Earth. Ranging data are often gathered infrequently during a long cruise stage as a cost-saving measure.

The more frequently scientists collect ranging data, the more precisely they could home in on Planet 9, Zwick said, as well as accomplishing other science unrelated to Uranus. The benefits of frequent data gathering would far outweigh the costs, the researchers argued.

Bucko acknowledged that his team's model was a simple proof of concept that considered only the gravitational influences of the Sun and outer solar system planets. The group plans to run more complex calculations that include the influences of other solar system bodies and hopes to test the model using data from NASA's New Horizons mission to Pluto, Soyuer said.

"I think it is great that people are thinking creatively about different ways in which we could eventually track down this elusive planet on the edge of the solar system," Brown said.

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

Solar Panels Nurse Desert Soil Back to Life

The carpet of the desert. A charismatic crust. A suit of armor.

Biological soil crusts go by many names. A living ecosystem of cyanobacteria, lichen, moss, and algae, the crusts grow on arid soils on all continents, even Antarctica. Biocrust coats 12% of the planet's surface and contains most of a desert's ecological diversity in just the top few centimeters of soil.

But the crust is easily broken (even a footstep can crush it), and operations such as ranching and farming have destroyed crust around the world.

Phoenix, Ariz., feels the toll. There, wind over fallow fields lofts dust hundreds of meters in the air, swallowing roads and blinding drivers. The dust also carries deadly fungi into the city.

Now, a group of scientists has found that solar farms could help accelerate recovery of soil crust by a factor of years. In a new study, the researchers assert that solar farms in the Phoenix metro area could serve as biocrust nurseries at little cost; a large-scale effort could supply enough biocrust to cover most of the fallow farmland in Maricopa County within 5 years (bit.ly/crustivoltaics).

"One wishes one would have thought of this a decade ago," said study coauthor and microbiologist Ferran Garcia-Pichel of Arizona State University.

Beach Umbrellas

The experiment began at a small suburban solar farm in the Sonoran Desert on the edge of Arizona State University's Polytechnic Campus in Mesa. Nestled between homes and a shuttered school, the small plant by Clearway Energy had operated for more than a decade.

Garcia-Pichel and his collaborators discovered biocrust naturally growing under the solar panels on the farm.

The scientists took photographs of the site following a rainstorm to compute the extent of the biocrust. Certain types of tiny photosynthesizing cyanobacteria that live in biocrust migrate to the soil surface after a rainstorm, creating easy-to-see green splotches that delineate biocrust from bare soil. Normally, cyanobacteria stay just a few tenths of a centimeter under the soil to protect themselves from extreme heat and abrasion.

The photographs revealed that biocrust cover underneath the solar panels was triple that of areas outside of the solar panels' shadows. Biomass underneath the solar panels was also double that of neighboring soil.

A dust storm crawls toward Phoenix in 2011. Healthy biocrust suppresses dust. Credit: Alan Stark/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Photovoltaic panels moderate the damaging ultraviolet rays of the Sun, explained Roger Rosentreter, an ecologist at Boise State University who was not part of the research. The solar panels were acting like beach umbrellas, reducing the temperature and water evaporation from the soil.

But the most exciting results came next, said study colead Ana Mercedes Heredia-Velásquez, a Ph.D. student at Arizona State University. Could solar panels become nurseries for new biocrust?

Crustivoltaics

Scientists have experimented with regenerating biocrust in laboratories or greenhouses for decades. Cultivated biocrust can be crumbled, sowed into bare soil, and wetted to grow healthy new crusts.

Existing efforts are small scale; they've each transplanted only some hundreds of meters of biocrust. The fallow lands of Maricopa County stretch for more than 750 square kilometers (300 square miles).

But solar farms are plentiful in the U.S. Southwest.

Heredia-Velásquez and her collaborators cultivated cyanobacteria in the laboratory from existing biocrust at the solar farm. They then removed biocrust under a group of solar panels and used it to inoculate 30 bare soil beds with cyanobacteria to see whether new biocrust would grow.

Over 2 years, biocrust grew to maturity under the solar panels without any intervention. In contrast, biocrust in plots without inoculation grew far slower, and the researchers estimated that biocrust would take 6–8 years to mature fully in those plots.

Hypothetically, solar farm biocrust could be harvested every 1–2 years, and 90% of the harvest could be used to regrow crust on bare land away from the solar farm. Ten percent of the harvest could be replanted, wrote the scientists.

Biocrust cover tripled underneath solar panels, and its biomass doubled.

The group dubbed the process crustivoltaics, an analogue of agrivoltaics, which appropriates solar panel land for agriculture.

"With crustivoltaics, thousands of [square] miles of dryland soils can be potentially restored in a relatively short period of time," said study colead and microbial ecologist Ana Giraldo-Silva of the Public University of Navarre in Spain.

Biocrust is cultivated in plots near Arizona State University's Polytechnic Campus in Mesa. Credit: Ana Mercedes Heredia-Velásquez

A Question of Scale

"Farming biocrusts under PV [photovoltaic] panels can be one step in our efforts to have a healthy planet," Rosentreter said. Biocrusts suppress dust, fix carbon dioxide in the soil, and provide soil nutrients like ammonia for plants.

Because the study was a proof of concept, there are more than a few outstanding questions. Biocrust organisms depend on certain soil and climate conditions; a crust in warm-weather Phoenix could have a completely different microorganism population than a biocrust in a colder location a few hundred kilometers away. Ideally, land needing restoration would have nurseries nearby to grow the best match.

Researchers studied this thin layer of biocrust that formed beneath solar panels in Phoenix, Ariz. Credit: Biodesign Institute/Arizona State University

"With crustivoltaics, thousands of [square] miles of dryland soils can be potentially restored in a relatively short period of time."

Microbiologist Nuttapon Pombubpa at Chulalongkorn University in Bangkok, Thailand, who did not participate in the study, praised the concept. But he warned against installing solar farms on protected land for their nursery potential. "We should be cautious about applying this technology to dry lands in natural habitats and national parks."

Pitching large-scale pilot projects to solar farms in Maricopa County is the next step, Garcia-Pichel said.

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

Hypoxia Affects One in Eight Rivers Worldwide

In March 2023, the *Guardian* reported a "wall of dead fish" blanketing Australia's Darling (Baaka) River. Bodies of belly-up cod, carp, and perch bumped against each other along a 10-kilometer (6-mile) stretch of river. It was a grim but not uncommon sight. This was the third fish kill in 4 weeks on Australia's third-longest river.

The culprit was hypoxia, a condition that occurs when the dissolved oxygen content of water dips below 2 milligrams per liter (2 parts per million).

It's generally assumed that the turbulence of rivers allows for adequate oxygen exchange with the atmosphere and that hypoxia is rare in rivers, but the phenomenon is far more prevalent than researchers previously understood.

A new study in *Limnology and Oceanography Letters* examined river samples from 95 countries and found low dissolved oxygen conditions in one in eight rivers worldwide (bit.ly/hypoxic-rivers).

The Power of Public Data

Scientists have tracked dissolved oxygen in rivers for decades. The new paper references a slew of studies from the past century, including a 1925 oxygen survey on the Ohio River in the United States and a 2018 report linking hippopotamus feces to Brazilian fish kills.

"There've been these examples [of hypoxia] from across the globe," said Joanna Blaszczak, a biogeochemist at the University of Nevada, Reno and lead author of the study. "What was missing was the synthesis of all of these different conditions and locations."

The study includes data from every continent except Antarctica and leans heavily on public government data sets. For data-scarce regions in South America and Africa, the researchers tapped into their networks to ask colleagues for information.

"It's so much more than the 10 people that were on this paper could ever possibly measure on our own," Blaszczak said of the joint effort. "It's incredible."

"It's so much more than the 10 people that were on this paper could ever possibly measure on our own."

The final analysis included 118 million paired observations of dissolved oxygen and water temperature taken from 125,000 river locations. The global analysis showed that a surprising 12.6% of river locations had at least one hypoxic measurement.

Hypoxia's Biggest Triggers

The prevalence of oxygen-starved rivers allowed the researchers to compare hypoxic conditions across climates, topographies, and watersheds.

Overall, the slowest and smallest rivers were the most at risk. Slow moving water has less turbulence, creating less opportunity for gas to be pulled from the air and dissolved. Shallow rivers have a low volume, meaning that less oxygen is available to aquatic life and the water is at greater risk of oxygen depletion.

The most significant predictor for hypoxia, though, was maximum water temperature. Aquatic life requires more oxygen in warm environments, and warmer water can hold less dissolved gas than colder water. Warm rivers therefore release oxygen back into the atmosphere just as aquatic life needs it most. Australian ecologists assumed that the recent Darling (Baaka) fish kills were caused in part by warm river temperatures, as well as an increase in fish populations competing for limited oxygen.

At the watershed level, the most common trait among hypoxic rivers was proximity to wetlands or urban centers. Wetlands and city streams tend to have slower and less turbulent flows. In both settings, there's also more organic matter, which can fuel the production of bacteria that devour dissolved oxygen. Rivers surrounded by wetlands or cities had a 15%–20% chance of experiencing hypoxia—much greater odds than rivers near forests, grasslands, or even agriculture.

An Undercount

"I really liked this study; it's the first, to my knowledge, to actually quantify the prevalence, the frequency, and the duration of hypoxia in rivers," said John Gardner, a hydrologist at the University of Pittsburgh. The results put a number on what researchers have otherwise just intuited, he said.

By spotlighting the prevalence of hypoxia in rivers, the study also encourages future research. "I think that it's just opening the door," Gardner said of the findings.

Even more rivers are likely affected by low dissolved oxygen. Roughly 90% of the locations in the study were on U.S. rivers, which now commonly house round-the-clock automated sensors to collect water observations. In many countries, river samples are collected manually and only periodically, providing only snapshots of conditions.

Likewise, manual sampling is often conducted during the day for the convenience of researchers. But dissolved oxygen dwindles

Small, low-gradient streams, such as the one pictured here in North Carolina, are some of the most susceptible to hypoxia. Credit: Joanna Blaszczak

High-frequency sensors deployed in a stream in Oak Creek in central Arizona provide continuous data that capture nighttime hypoxic conditions. Credit: Joanna Blaszczak

overnight once photosynthesis stops. Blaszczak and her colleagues found that daytime-only water samples missed approximately 25% of hypoxic rivers.

"I really liked this study; it's the first, to my knowledge, to actually quantify the prevalence, the frequency, and the duration of hypoxia in rivers."

The study has a heavy bias toward U.S. data, which the researchers recognized. But the findings still demonstrate a surprisingly prevalent problem. If current data show that one in eight rivers experiences short-term hypoxia, that rate will only increase as round-the-clock monitoring becomes more available around the world.

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

Harpy Eagles Concentrate Precious Nutrients in the Amazon

The Amazon is home to a contradiction: The extremely biodiverse rain forest thrives on nutrient-poor soil.

New research provides a clue to the conundrum: Unlike plants, animals of the rain forest move around, shifting nutrients as they go.

In a recent study, scientists found that harpy eagles bring nutrients to their nests, creating localized hot spots and potentially affecting soil biogeochemistry (bit.ly/eagle-nutrients).

A Jaguar's Weight in Nutrients

Harpy eagles are apex predators in the rain forests of Central and South America, hunting for such prey as sloths, monkeys, and other birds in the forest canopy. The eagles often pair for life and rear one or two chicks at a time in large platform nests built 30–50 meters (100–160 feet) above the ground. Chicks spend their first 1–2 years in the nest, during which time their parents bring prey for them to eat.

Researchers installed camera traps at harpy eagle nest sites in the state of Mato Grosso in Brazil and found that each pair of birds transported more than 100 kilograms (220 pounds) of prey to their nest each year—that's more than an entire jaguar's weight in carcasses.

"We wanted to find out whether harpy eagles could be increasing the presence of nutrients in soils and vegetation around their nest trees," said ecologist Everton Miranda of the Peregrine Fund. Miranda is the lead author of the study.

From Death, New Life

Most of the prey brought to the nest is eaten by the parents and chicks, but leftovers often fall to the ground, along with lots of eagle poop. The combination of carcasses and excrement introduces scarce and vital nutrients such as phosphorus around nest trees, and plants are quick to take advantage.

Researchers installed camera traps and found that each pair of birds transported more than an entire jaguar's weight in carcasses to their nest each year.

Using a rope chainsaw, Miranda and his colleagues collected leaves from the nest

A 1-day-old harpy eagle chick in Paranaíta, Mato Grosso, Brazil, waits for food. New research investigated how harpy eagle droppings influence the flow of nutrients around nests. Credit: Everton Miranda/SouthWild.com

Harpy eagles are apex predators that bring prey, including sloths and other birds, to their nests. Credit: cuatrok77/flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

trees and the surrounding rainforest understory and canopy, as well as leaves from distant areas. They found that nutrients, including nitrogen and phosphorus, were much more abundant in the understory and canopy near harpy eagle nests than in the vegetation far from nest trees. Levels of nitrogen were 87% higher in leaves surrounding nest trees, and levels of phosphorus were 142% higher.

An Uncertain Path from Eagle to Tree

It's not surprising that the nutrients being brought in by harpy eagles are ending up in the flora around their nest trees, said Chris Doughty, an ecologist at Northern Arizona University who was not involved in the study. "I think the study makes a convincing argument that nutrients from harpy eagle kills and droppings are making it into the vegetation around their nest trees," he said.

But how these nutrients are making it into the trees is not quite clear. Scientists understand very little about how nutrients cycle through an ecosystem, especially in diverse tropical forests, Doughty said.

One route could be through the soil, but to their surprise, the researchers did not find elevated nutrient levels around nest trees. When he initially saw soil data from the nest trees, Miranda nearly concluded that harpy eagles had no significant effects on local nutrient cycles. Then he analyzed the tree leaves and found the missing nutrients in the plant life.

Nutrients Flow...

One caveat to keep in mind is that the soil measurements in the study were made at a single time point, said Julia Monk, a community and ecosystem ecologist at the University of California, Berkeley who was not involved with the study. "It's possible that capturing soil nutrient influx and outflow over longer periods of time...could help us really understand what's going on."

Everton Miranda, shown here with a harpy eagle, led the new study. Credit: Everton Miranda

Doughty agreed that if the nutrients are passing through the soil en route to the trees, one-time measurements may not capture their presence in the soils. "Biologically important elements like phosphorus can cycle incredibly rapidly through ecosystems," he said. "Oftentimes, it can seem like they are not even really entering the soil because they are being taken up so rapidly by [fungi] and roots."

...Through Leaf and Bark?

But some of the nutrients from harpy eagle leavings could be taken up directly by the vegetation around nest trees through leaves or bark before reaching the soil. Eagle poop often sprays the foliage beneath the nest, according to Miranda, which could allow the plants to intercept at least part of the nutrient input from harpy eagles before it reaches the soil.

Monk agreed that the vegetation around nest trees could be directly absorbing some of the nutrients, but she also said that some nutrients could reach the soil and then be absorbed by the trees. "The two ideas are not mutually exclusive," she said.

Even though it's unclear how nutrients are getting from harpy eagle kills and droppings to trees, "the data are quite convincing that the transfer is happening," Doughty said.

"The loss of these eagles could have profound effects on Amazon biodiversity."

These findings highlight the important role harpy eagles play in the Amazon ecosystem: By concentrating nutrients in a relatively small area, the birds increase heterogeneity in the rain forest landscape. "Environmental heterogeneity is one of the main predictors of biodiversity," Miranda said. "The loss of these eagles could have profound effects on Amazon biodiversity."

By **Adityarup Chakravorty** (chakravo@gmail.com), Science Writer

In the Pacific Northwest, 2021 Was the Hottest Year in a Millennium

In the summer of 2021, a historic heat wave baked the Pacific Northwest. A heat dome stalled over the United States and Canada, causing temperatures to soar to 40°C–50°C (104°F–121°F). More than 650 people died, infrastructure buckled, agricultural fields withered, wildfires were sparked, and forests were damaged.

"It was incredible," said Karen Heeter, a dendrochronologist at Lamont-Doherty Earth Observatory at Columbia Climate School. That summer, Heeter was finishing her doctorate at the University of Idaho while living in a brick building with no air conditioning. "That experience was the jumping point for me," she said, and she decided to investigate the history of heat in the Pacific Northwest.

Dendrochronologist Karen Heeter takes a core of a mountain hemlock at Crater Lake, Ore. She and her colleagues combined cores from live and dead trees to produce 1,000 years of climate history in the region. Credit: Grant Harley

In a new study in *npj Climate and Atmospheric Science*, Heeter and her colleagues used tree ring records from the Pacific Northwest to reconstruct summer temperatures for the past 1,000 years (bit.ly/tree-ring-heat). They found that 2021 was a scorcher—hotter than any other year in the past millennium. The data hint at a future full of heat waves.

A Millennium of Temperatures

Tree rings capture years of climate signatures: temperature, soil moisture, and wind stressors. A tree records summer temperature in the density of its rings. Typically, denser rings mean warmer temperatures.

Heeter and her colleagues collected cores from 29 conifer trees in the United States and Canada. "In the Pacific Northwest, there are long-lived species of Douglas fir and mountain hemlock," said Heeter, adding that land preservation efforts helped protect these old trees. To extend the record further back, the team also sampled dead wood.

To make sure they had a continuous record, the researchers overlapped the cores from dead and live trees. Tree rings are like barcodes, and comparing the codes is like pattern matching, Heeter explained. "Wherever they match up, you can validate the dates. Once you're confident in that, you can keep pushing it back in time."

Using a method called blue intensity, the team measured ring densities to infer past temperatures. Heeter described blue intensity as "very, very up-close remote sensing," in which the blue wavelet of the visible light spectrum is reflected off the tree ring and measured. The reflectance of a ring's surface is related to the ring's density and is used as a proxy for the average ambient summer temperature during the year that ring grew. A tree does most of its growing during the summer.

From the rings, the researchers determined that Pacific Northwest conifers grew throughout temperature fluctuations over the past 1,000 years, though there has been significantly more warming in the past few decades.

Heeter said that since at least 1000 CE—as far back as the samples recorded—the Pacific Northwest has experienced prolonged periods of warmer-than-average temperatures. "But if you are comparing the magnitude, we're much warmer now than we were back then," she said.

A Hot Future

The team took the research a step further, using its 1,000 years of data to simulate future climate with the Coupled Model Intercomparison Project Phase 6 (CMIP6) under two different emissions scenarios.

The tree ring data indicate that the 2021 Pacific Northwest heat wave, which reached 3.6°C (6.5°F) above the 1951–1980 average, was a 1-in-1,000-year event. However, "we found the 3.6°C anomaly becomes so much more likely to happen within the next couple of decades," Heeter said. The future climate simulation showed that with intermediate levels of emissions (Shared Socioeconomic Pathways 2–4.5), the Pacific Northwest will have a 50% chance of experiencing a heat wave each year over the next few decades.

"This is really a step forward," said Irina Panyushkina, a dendrochronologist at the University of Arizona who was not involved in the study.

As a check, the team compared the modeled temperatures, the measured near-surface air temperatures from 1950 to 2021, and the 1,000-year tree ring temperature record and found good overlap. Because there are lots of uncertainties in modeling, this check was a way to confirm that the modeling approach was good, Panyushkina said. "It shows that the prediction is quite accurate." The researchers' approach could be used in other areas around the world, she added, even expanding to the hemisphere scale.

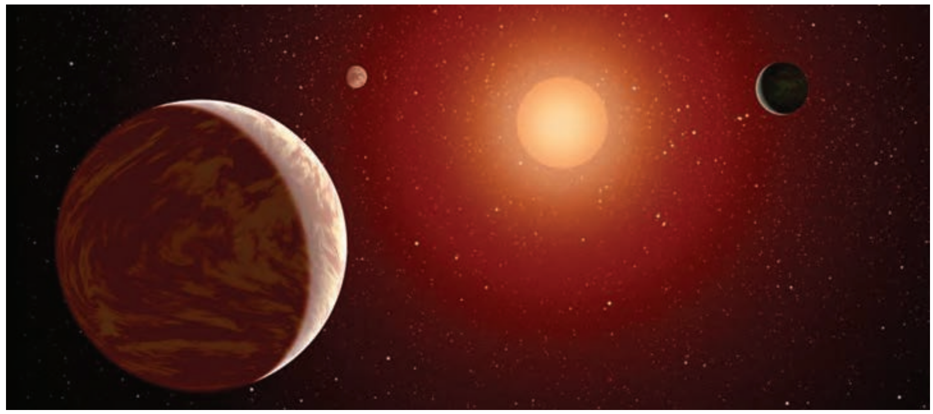
The likelihood of future heat waves has important implications for ecosystems and human health. Frequent and extreme heat will continue to put stress on the environment, people, and infrastructure. Heeter said she's already seen trees in heat distress in the Pacific Northwest. "The rate of change at which the Pacific Northwest is warming is really striking," she said, adding that trees cannot adapt to abrupt temperature rise.

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

Exoplanets May Support Life in the Terminator Zone

In the search for extraterrestrial life, scientists are looking in some pretty unusual places. Now, a new study reveals that some exoplanets orbiting red dwarfs could support life in the zone of near twilight between their dayside and nightside. The results were presented at AGU's Fall Meeting 2022 and published recently in *The Astrophysical Journal* (bit.ly/terminator-zone). The finding could widen the search for habitable planets in the universe.

"Habitable planets won't necessarily be habitable everywhere on their surface but, rather, could have habitable regions," said Ana Lobo, a postdoctoral researcher at the University of California, Irvine and lead author of the study.



An artist's rendering shows exoplanets orbiting a red dwarf star. Credit: NASA/JPL-Caltech

Stuck in the Middle

Red dwarf, or M dwarf, stars are common, making up about 70% of stars in the Milky Way. Because they are smaller and dimmer than the Sun, they have a closer-in habitable zone than stars like our Sun do.

Since 1995, more than 5,000 exoplanets have been discovered. In January, NASA's James Webb Space Telescope (JWST) detected its first rocky Earth-like exoplanet circling a red dwarf star, eliciting much excitement about its potential to host life.

Because of strong gravitational forces, exoplanets in M dwarf habitable zones often rotate at the same rate they orbit their host stars. The condition, called tidal locking, causes these planets to have a permanent dayside (facing the star) and nightside (facing away from the star).

The daysides are too hot for life as we know it, and the nightsides are too cold. But the narrow transition between light and dark—the terminator zone—may be at just the right temperature for water to flow, an essential condition for life as we know it.

"This concept of terminator habitability is not new," noted Rory Barnes, an astrophysicist at the University of Washington who wasn't part of the research. "That said, this work is a significant upgrade."

Lobo and her colleagues used a global climate model to simulate conditions on Earth-like exoplanets orbiting M dwarf stars. They explored both ocean-covered planets and water-limited planets, adjusting rotation rates and the distances between planets and their stars.

The researchers showed for the first time that terminators could sustain life on water-limited planets but not on ocean worlds. A marked contrast in dayside and nightside temperatures is essential to a habitable terminator, according to the researchers.

Water-rich planets lack this characteristic because heat in their atmospheres is efficiently transported from one side of the planet to the other, resulting in a more homogeneous climate and, at best, a meager difference between dayside and nightside temperatures.

For ocean-covered planets that are very close to their star (inward of the habitable zone), incoming stellar radiation heats the water on the dayside, turning it into water vapor, a greenhouse gas. A thick layer of water vapor traps heat, driving a runaway greenhouse effect wherein the entire planet is too hot for life.

On the other hand, the atmospheres of water-limited planets are less effective at moving heat, thus favoring a temperate climate at the terminator. Somewhere between too hot and too cold is just right.

"Planets with terminator habitability are a great illustration of how a wide range of climates can coexist on a planet," Lobo said.

"As humanity seeks to understand its place in the universe, it's intrinsically valuable to know what may or may not be different between Earth and other types of habitable worlds," Barnes observed. "This study helps astronomers and astrobiologists find life among the stars." Knowing just where to look for life can help scientists make better use of telescope time, he added.

A Twist in the Terminator Tale

The study shows that cooler ocean-covered worlds that are farther from their host star might eventually transition into water-limited planets with terminator habitability. Water that evaporates on the dayside of these water-rich planets is transported to the nightside, where it precipitates out as snow and forms large glaciers, trapping water on the nightside. Over time, the dayside would become drier, the researchers said.

"I think that's a really interesting prediction," said Stephen Kane, a planetary astrophysicist at the University of California, Riverside who wasn't involved in the study. "It creates a very self-consistent picture, which I like, and that'll be something we'll be able to test." With the JWST making ever more advanced measurements, scientists are inching closer to detailing the atmospheres of exoplanets, he added.

"The terminator habitability concept sounds so unusual, but I just love this idea of having everything on the table as a possibility," Kane said.

The study's findings open the door to a whole new class of planets that astronomers can search for signs of life, Lobo said. "It's an exciting change in direction."

By **Alakananda Dasgupta** (@AlakanandaDasg1), Science Writer

Climate Change Knocks It Out of the Park

Teams that play mostly day games in open-air stadiums like the Chicago Cubs' Wrigley Field (left), are projected to see the greatest increase in home runs as climate change brings more unseasonably warm days. Teams playing in domed stadiums like the Tampa Bay Rays' Tropicana Field in Florida (right), as well as teams that play mostly night games, are largely immune to temperature-related increases in home runs. Credit: Rex Hammock (left) and Eric Kilby (right), both CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Home runs have been getting steadily more common in baseball for decades, and a recent spike might be driven by anthropogenic climate change.

A new analysis combines decades of baseball statistics and ballistics data with predictive climate modeling. The study shows that more than 500 home runs since 2010 can be attributed to climate-driven, unseasonably hot temperatures. If climate change keeps warming the globe, some teams will continue to see more home runs while others will remain largely unaffected.

"I'm a baseball fan and I'm a climate scientist, too," said lead researcher Christopher Callahan, a doctoral student in geography at Dartmouth College in Hanover, N.H.

The idea for this research came from an established physics concept: When it's hotter

Ballistics helped the researchers isolate the impact of temperature on the number of home runs.

outside, the air gets a little bit thinner. This is hardly noticeable, unless you're a 100-mile-per-hour baseball rocketing toward the outfield.

"I was curious about whether you could see this in the large-scale data, and it turns out that you can," Callahan said.

Going, Going, Gone!

Callahan and his colleagues analyzed temperature trends and home runs from more than 100,000 Major League Baseball (MLB) games from 1962 to 2019. They also included advanced ballistics data on more than 220,000 batted balls from 2015 to 2019 using baseball's high-speed Statcast camera system. Ballistics allowed the researchers to account for the effects of playing in different stadiums and to compare batted balls of the same launch angle and speed. This helped them isolate the impact of temperature on the number of home runs.

The researchers then combined these baseball analytics with predictive climate models, allowing them to calculate the likelihood that anthropogenic climate change, rather than a random temperature anomaly, caused a day to be unseasonably hot.

The analysis showed that for every 1°C increase in temperature, there was a roughly 2% increased chance per game that a fly ball would be a home run. A total of 577 homers from 2010 to 2019 can be attributed to human-caused warming—that's an average of about 58 per year. Looking forward, the researchers predicted an increase of around 95 home runs per season for each 1°C increase in temperature.

"It's a real signal of the way that climate change is having such a pervasive impact," Callahan said, "and an impact on things that are not just hurricanes and heat waves, but more subtle changes in every part of our lives."

"It's a real signal of the way that climate change is having such a pervasive impact."

Not every baseball field will see the same increase in home runs. "Wrigley Field will have the most increase in home runs in the future, because it mostly [hosts] day games when the temperatures are hottest," Callahan said, "whereas in places that play mostly night games, the temperatures are a lot milder, so you will have less of an increase."

On the other end of the spectrum, "Tropicana Field in Tampa Bay [Florida] is covered all the time. It's the only nonretractable dome in baseball, and so it's the one place where this is just not going to be a problem," Callahan said.

The results were published in the *Bulletin of the American Meteorological Society* (bit.ly/baseball-climate).

The Climate Changeup

Callahan explained that the analysis was possible because baseball is such a data-rich environment. "That's great from our perspective—it's a real treasure trove." But the project also hints at the hidden effects of climate change that are undiscoverable because data are lacking, he added.

"It really illustrates that there are times when we end up looking for our keys under the lamppost because that's where the light is," Callahan said. Future work will explore how climate-driven heat also affects player performance.

"I don't know that we've seen a baseball game canceled for heat yet, but I think it's coming."

Jim Albert, a statistician at Bowling Green State University in Ohio, noted that although these results are statistically significant, the number of home runs attributable to climate change is small relative to other ball and player effects.

Albert, who was not involved with the new analysis, contributed to MLB-commissioned reports that investigated the recent rise in home runs. The new results "are similar to our findings on the effect of temperature," he said. "The novel aspect of this paper is the exploration of the effects of global warming on home run hitting."

Callahan speculated that there will likely come a point when team owners decide that the increase in home runs isn't worth the heat-related health risks to players and fans. "I don't know that we've seen a baseball game canceled for heat yet, but I think it's coming," he said.

Teams might opt to shift from day games to night games, invest in a domed stadium, or even relocate to a cooler city—mitigation strategies that could have profound economic impacts on a region.

"If the effects of global warning increase as the authors predict," Albert said, "then I believe MLB should use this information in future plans about scheduling of games and the construction of the ball."

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

Dating the World's Tallest Trees

Coast redwoods may be the tallest trees in the world, but just the tiniest samples of their wood can reveal the past. Researchers recently analyzed thousands of pencil-width cores extracted from living trees and deadwood to construct a set of annually dated tree ring chronologies for coast redwood, the first such database of its kind. These records, which stretch back to the 4th century, will allow scientists to pinpoint the precise timing of climate changes, earthquakes, and other environmental phenomena.

Climbing for Science

Between 2005 and 2021, researchers working in California and Oregon collected tree cores from hundreds of coast redwoods (*Sequoia sempervirens*). Each extraction was a massive undertaking, said Allyson Carroll, a dendrochronologist at California State Polytechnic University, Humboldt who led the new analysis. That's because rather than just walking up to a tree and collecting a single core, as is commonly done in dendrochronological studies, the researchers donned climbing gear and ascended via free-hanging ropes to collect cores every 10 meters along a tree's trunk.

Acrophobia is clearly a foreign concept in this line of work—the redwoods towered up to 116 meters (380 feet) tall.

It could take the better part of a day to rig just one tree with ropes and collect cores from it, said Steve Sillett, a botanist at California State Polytechnic University, Humboldt who did a lot of the climbing. Each core, measuring 0.5 centimeter (0.2 inch) in diameter, was drilled by hand using an instrument called an increment borer. "It's a lot of physical work," Sillett said. "By the end of the day, our arms are sore."

To transport the cores safely back to the ground, the team placed them in rigid cases that they nestled within drawstring bags. But extracting a core and maneuvering it into a case is a delicate dance, particularly when a core is brittle, Sillett said. "Sometimes they do drop, and it's excruciating."

A Puzzle in Wood

Carroll spearheaded the analysis of the team's roughly 6,000 cores. Each cylindrical sample revealed a sequence of tree rings, and Carroll's first step was to crossmatch the sequences obtained at different heights from a single tree. That was harder than it sounds, said Carroll, because the rings of *Sequoia sempervirens* don't always grow uniformly along a tree's entire vertical extent.

It's relatively common in these trees that a ring just disappears at some point, said Evan Larson, a dendrochronologist at the University of Wisconsin–Platteville who was not involved in the study. Sequences from the same coast redwood can have huge discrepancies in their numbers of rings, he said. "Sometimes it's a dozen or more."

For each of the 278 trees sampled, Carroll used visual and computer-aided matching

Coast redwoods—the world's tallest trees—record information stretching back to the 4th century in their rings. Credit: Richard Masoner/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Tree ring cores extracted from a coast redwood growing in Muir Woods National Monument in California hold centuries of data. Credit: Allyson Carroll

to compare patterns of ring widths and determine a complete growth sequence. She ascribed a calendar year to each tree ring by identifying sequences of so-called marker years—rings that are characteristically thicker or thinner or otherwise altered and correspond to independently dated events such as droughts or fires—and then counting forward or backward in time.

“I can’t imagine the complexity of the puzzle that they had to put together.”

In all, Carroll tabulated more than 1.2 million rings. Keeping all of those measurements straight was no doubt an enormous amount of work, said Bryan Black, a dendrochronologist at the University of Arizona in Tucson who was not involved in the research. “I can’t imagine the complexity of the puzzle that they had to put together.”

Carroll next stitched together the growth sequences of different trees growing within a kilometer or so of one another. It’s most valid to compare trees growing in geographic proximity, Carroll said, because they experience a similar climate, which is a major driver of ring growth.

Carroll divided the team’s samples of trees into 47 regions and assembled a ring chronology for each region. Those records ranged in length from 86 to 1,687 rings, with the oldest ring—from a tree in Redwood National Park, near Orick, Calif.—corresponding to the year 328 CE, the team reported in *Dendrochronologia* (bit.ly/sampling-sequoias).

Sleuthing for an Earthquake

Coast redwoods have long stood sentry in a complex ecosystem shaped by fire, drought, and fog. Many of those environmental drivers can be recorded in tree rings, Larson said, and redwoods can accordingly provide a record of long-term climate change.

The new chronologies—more than half of which stretch back at least 500 years—are critical for determining when specific environmental changes occurred, Larson said. “There’s the ability to expand perspectives beyond human timescales.”

Carrol and her team are already planning to use one of their regional chronologies to investigate a mysterious earthquake. They will sample wood from near California’s Harold Richardson Redwoods Reserve in Sonoma County to constrain the date of an earthquake that occurred on the northern San Andreas Fault between the 17th and 19th centuries.

The temblor was the last big event on the San Andreas before the famous 1906 earthquake, which decimated much of San Francisco. Ground shaking can cause trees to break or bend, and the researchers will sample and date wood to look for patterns of consistent damage that might have been wrought by an earthquake.

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

EPA Air Pollution Proposal Stirs Debate

EPA is considering changing the National Ambient Air Quality Standard (NAAQS) for annual $PM_{2.5}$ from 12 micrograms per cubic meter (μg/m^3) to 9–10 averaged over 3 years. These guidelines would align with the latest science suggesting adverse health effects for people exposed to PM2.5—airborne particles smaller than 2.5 micrometers (30 times smaller than the diameter of a human hair).

Some industry groups called the proposed standards unnecessary, whereas environmental and justice groups criticized EPA for not going far enough.

But the agency also said it would take public comments on revising the standard to as low as 8 μg/m^3 or as high as 11 μg/m^3. The agency opted to keep the 24-hour $PM_{2.5}$ concentration standard of 35 μg/m^3.

Lowering the EPA guidelines would force utilities, manufacturers, and farmers to upgrade factories, practices, and equipment to release less pollution.

Some industry groups called the proposed changes unnecessary, whereas environmental and justice groups criticized EPA for not going far enough.

Each year in the United States, twice the number of people die from causes related to air pollution than from car crashes. Tighter guidelines would particularly benefit Black, Hispanic, and low-income communities, which face the brunt of air pollution.

Human Health Risk

When inhaled, the particles travel deep into the lungs, infiltrating the alveoli and traveling into the blood. $PM_{2.5}$ is thought to accumulate in the lungs over time, causing inflammation.

The particles have been linked to myriad health issues, including asthma, preterm birth, heart disease, respiratory infections, and premature death. Each year in the United States, $PM_{2.5}$ causes nearly 11,000 excess deaths, nearly 3,000 incidents of lung cancer, and 18,000 morbidities, according to data from New York University's Marron Institute of Urban Management dashboard.

Burning gasoline, oil, diesel fuel, or wood releases $PM_{2.5}$ particles. Electric utilities and industrial boilers are responsible for about half of the direct $PM_{2.5}$ pollution in the United States. Another 40% comes from industrial equipment such as metal smelters, petroleum refineries, and cement kilns. Tilling, harvesting, and applying fertilizer and manure create additional pollution from agriculture. Cars and trucks also release fine-particle pollution.

Once aloft, these particles can stay in the air for long periods and travel far.

When inhaled, the particles travel deep into the lungs, infiltrating the alveoli and traveling into the blood.

Mount Baker frames an oil refinery in Washington. Credit: Walter Siegmund/Wikimedia Commons, CC BY 2.5 (bit .ly/ccby2-5)

Passed in 1970, the Clean Air Act requires EPA to set standards for particulate matter and five other pollutants. EPA must periodically review the standards to ensure adequate health and environmental protection.

The agency has updated either the annual or the short-term $PM_{2.5}$ standard about every decade since the 1990s. But in December 2020, the Trump administration opted to keep standards the same.

The Biden administration said it is now reconsidering the limits because the latest science suggests that the current standards don't adequately protect public health.

Roughly 8,800 more people could be saved an asthma diagnosis in 2032 if the limit is set at 8 μg/m3 rather than 10 μg/m3, according to EPA's Regulatory Impact Analysis published in late 2022. In the same analysis, EPA estimated that 7,500 deaths would be avoided in 2032 if levels were below 8 μg/m^3 versus 10 μg/m^3.

In EPA's 2019 Integrated Science Assessment, the agency reviewed the most recent animal toxicology studies, controlled human exposure studies, and epidemiological studies and found that the evidence supported and strengthened the health findings from past research.

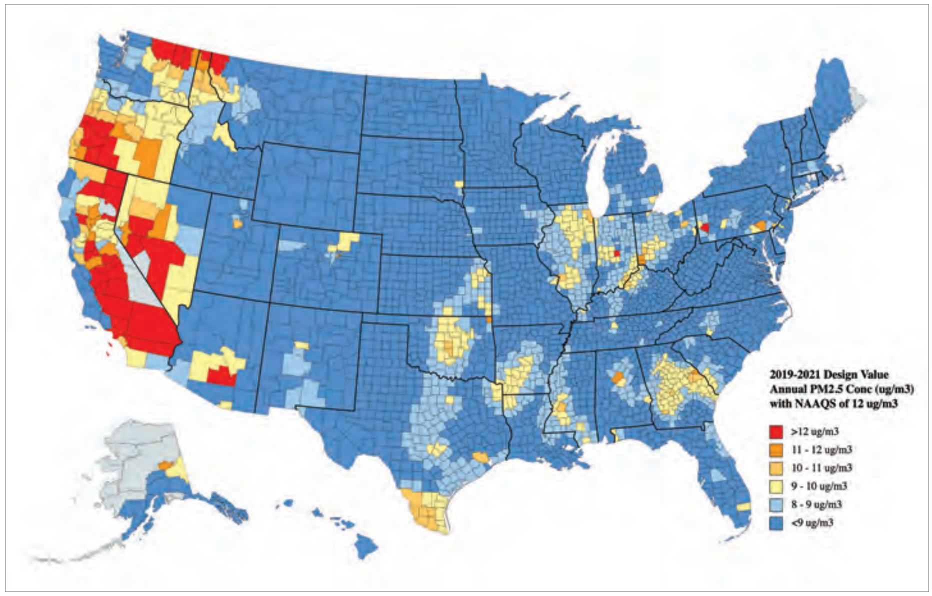
Science Shows Environmental Injustices

The agency found "strong evidence" that Black and Hispanic populations, on average, experience higher $PM_{2.5}$ exposures and related health risks than non-Hispanic white populations. It also found that people in lower socioeconomic positions are exposed to higher concentrations.

Annual $PM_{2.5}$ concentration was 14% higher for Black people in the United States than for white people in 2016, according to a study published in *Nature* in 2022 (bit.ly/pollution-disparities).

EPA's Regulatory Impact Analysis predicts that lowering the annual $PM_{2.5}$ standards will lessen pollution exposure for marginalized groups, particularly if limits are lowered to 8 $\mu g/m^3$. Hispanic people would experience 4.8% less $PM_{2.5}$ pollution at 8 $\mu g/m^3$; at 10 $\mu g/m^3$, the change drops to 1.5%. Asian people would see similar relief.

A *New England Journal of Medicine* study found that if the standard were lowered to 8 $\mu g/m^3$, there would be a 6% decrease in exposure for low-income Black and low-income white adults.



Annual $PM_{2.5}$ concentrations in micrograms per cubic meter ($\mu g/m^3$) in U.S. counties show that lowering the standards will affect areas across the country. Credit: MapChart, Data from EPA's Air Quality System (AQS) database

Environmental and Health Organizations Debate Limit

Wide-sweeping policies such as the $PM_{2.5}$ rule affect human health, governmental regulation, and industrial activities. While EPA deliberates, opinions about the best level for $PM_{2.5}$ standards are swirling.

The Clean Air Scientific Advisory Committee, an independent panel of experts that provides advice to EPA regarding the NAAQS, recommended that the annual average should be between 8 and 10 $\mu g/m^3$.

The American Lung Association said EPA's proposal to limit pollution to 9–10 $\mu g/m^3$ "misses the mark" and called for an 8 $\mu g/m^3$ annual limit and a 24-hour limit of 25 $\mu g/m^3$. The World Health Organization (WHO) recommended that standards be set at an annual limit of 5 $\mu g/m^3$ and a 24-hour limit of 15 $\mu g/m^3$. Implementing WHO's standard worldwide would prevent almost 80% of deaths associated with $PM_{2.5}$, according to research by WHO.

Environmental groups argued that the proposed standards don't go far enough. Earthjustice, a progressive environmental nonprofit, said the proposed regulation fails to make the sweeping improvements called for the latest science.

"With $PM_{2.5}$, EPA knows that kills people," said Seth Johnson, a senior attorney at Earthjustice. "And for $PM_{2.5}$, the evidence of disparate impact is really strong. We know it affects people of color—particularly Black people—at least in part due to differences in exposure."

Industry Weighs In

Currently, 12 cities have annual $PM_{2.5}$ levels above today's EPA standard. If the limit is lowered to 9 $\mu g/m^3$, at least 32 cities will exceed the standard.

Though industry groups have concerns about financing the implementation of new standards, EPA must consider in its decision only what protects human health and welfare.

Lowering the limit will be a harmful burden for the manufacturing industry, according to a statement from the trade association National Association of Manufacturers (NAM).

"Let manufacturers do what they do best: innovate and deploy modern technologies to protect the environment, while creating jobs and strengthening the economy," said NAM president and CEO Jay Timmons in a press release.

The Fertilizer Institute, an advocacy organization for that industry, stated that the new standards would threaten the production of fertilizer domestically. Nisei Farmers League in California said in a statement that many farmers are still working to comply with the current standard and that doing so requires new equipment and production systems.

Lowering the standard to 11 $\mu g/m^3$ would be challenging for industries, especially in places where monitored concentrations are already high, but "it wouldn't cause large-scale impacts across the country," wrote Leslie Fifita and Robynn Andracsek of Providence Engineering, an engineering and environmental consulting firm in Louisiana and Texas, in an email. "However, a reduction down to 8 $\mu g/m^3$ would create complex compliance issues with respect to $PM_{2.5}$ attainment areas, air permitting, and air dispersion modeling."

"With $PM_{2.5}$, EPA knows that kills people."

With scientific findings suggesting larger public health benefits from lower $PM_{2.5}$ levels, as well as concerns from industry groups about reaching the standards, time will tell which value of $PM_{2.5}$ EPA will settle on. The agency hosted a public 60-day comment period and hearings this past spring, and the final decision may come later this year or next.

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

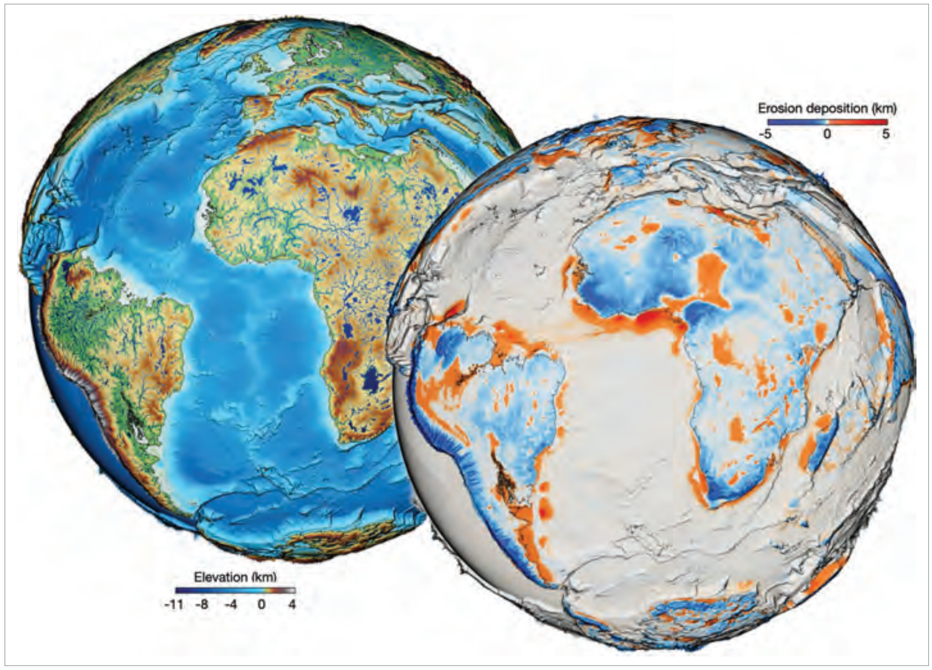
One Surface Model to Rule Them All?

Earth's complex and varied surface is shaped by myriad natural processes, from deep-seated faults thrusting mountains skyward to rivers carving valleys and carrying sediment to the ocean. To develop a fuller picture of how our planet's outer layer has evolved, geoscientists piece together the interactions among these processes with geological models.

But like a puzzle with missing pieces, existing models have given only a patchy understanding of Earth's past 100 million years.

Now, researchers have developed a high-resolution, continuous model of Earth's geologically recent evolution. The advanced model can inform scientists about our planet's long-term climate and biological changes, how today's landscapes were formed, and how millions of tons of sediment were dumped into the ocean.

"This is a significant technical advance, as it provides for the first time a global perspective on the relationships between sediment transfer and Earth's physiographic changes," said Tristan Salles, a senior lecturer in geosciences at the University of Sydney in Australia and lead author of a new *Science* paper introducing the model (bit.ly/landscape-dynamics).



A new model traces global landscape dynamics across 100 million years. In this still, sediment flow is represented in blue (erosion) and orange (deposition). Credit: Tristan Salles, University of Sydney

Reading the goSPL

Computer-based methods for reconstructing landscape evolution have been used since the 1990s. Geomodeling software also has been a familiar tool for interpreting geological data, building 3D models of Earth's surface, and simulating the evolution of landscapes over time.

The team collated these technologies with a model using a recently released software tool some of the coauthors developed called goSPL (global scalable paleo landscape evolution). The model evaluates the evolution of Earth's surface, considering interactions among tectonics and processes in the mantle, hydrosphere, and even atmosphere.

goSPL was built using data based on the physics of surface processes, sediment accumulation maps, tectonic movement, and climate trends of the past. The research team then improved the accuracy of the model's predictions by calibrating it with present-day observations from rainfall and water flows.

The simulations yielded high-resolution maps showing the physical landscapes and water drainage networks of Earth on a global scale for the past 100 million years. The simulation boasts a spatial resolution of 10 kilometers (6 miles), broken into million-year frames.

"We combined various information and observations from present-day rivers' sediment and water fluxes, drainage basin areas, and seismic surveys, as well as long-term local and global erosion trends," Salles said.

Monumental Takeaways

The simulations show mountains rising and falling, continents shifting, and sediment moving from land to ocean. By better visualizing sediment flow, for instance, they clarify upstream dynamics as well as the development of basins and other landscapes downstream. In one example, the simulation shows how river channels and tributaries in South America's Paraná Basin have changed position under the influence of tectonics and climate.

"The Salles et al. study represents an exciting achievement."

"The Salles et al. study represents an exciting achievement," said geomodeler Charles Shobe of West Virginia University, who noted three major advances in the study. "Firstly, they successfully work at the global scale, whereas we typically run these sorts of models at the watershed to mountain range scale," he explained. "Secondly, their approach incorporates detailed tectonic and climatic reconstructions that allow for inputs like tectonic plate motion and precipitation.... Thirdly, they successfully 'nudge' their model to make sure it stays true to reconstructions of past topography," Shobe said.

If the past is the key to the future, this one model could help scientists foresee phenomena as varied as how oceans will evolve in response to climate change, the impact of tectonics, and how sediment transport will regulate our planet's carbon cycle.

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

The Vanishing Scholar: Indigenous Erasure in Funding Data

Throughout its history, the United States has pursued two main objectives through federal Indian law and policy: the assimilation of the country's First Peoples and the dispossession of their land. Both objectives have worked toward the ultimate goal of erasing Indigenous Peoples [*Newland*, 2022]. Laws and policies serving this goal have repercussions across all aspects of the lives of Indigenous Peoples, through influ-

The erasure of Indigenous Peoples has long led to their underrepresentation across academic fields, especially in the environmental sciences.

ence whether on our representation in popular culture (or lack thereof) or on the research initiatives and funding opportunities that are accessible to us.

Such policies are clearly not a thing of the past; they continue to be part of an ongoing process of settler colonialism that is furthering the erasure of the First Peoples and first scientists of this country. Recent polling by the Native-led nonprofit organization IllumiNative indicates that 78% of Americans "know little to nothing about Native Americans and a significant portion believe that Native Peoples must be a dwindling population because they do not see, hear, or read about Native Peoples." These sentiments are not new and echo, a century later, those embodied in photographer Edward Curtis's early 20th-century "Vanishing Race" project, wherein he sought to document Native American lives and cultures, which he mistakenly thought would fade from existence.

The erasure of Indigenous Peoples has long led to their underrepresentation across academic fields, especially in the environmental sciences. This field continues to be among the least diverse in the United States, with more than 67% of degrees in 2019 awarded to white students and only 20% awarded to Latinx, Asian, Black, Indigenous, and Pacific Islander students combined, according to U.S. Department of Education data compiled by Data USA. The geosciences exhibit similar trends in their lack of diversity.

All the work that environmental scientists, ecologists, and geoscientists do in the United States inherently involves Indigenous lands, so it is critical that scientists examine how this work is done, who is represented through it, and who has access to do the work in the first place.

In a recent study, *Chen et al.* [2022] detail patterns that suggest systemic racial disparities in the success rates of proposals funded by the National Science Foundation (NSF) across all its directorates. The authors examined funding rates for principal investigators (PIs) from 1996 to 2021 using NSF data extracted from publicly available annual reports. Notably few, or even absent for certain years, are data on Indigenous scholars. These omissions are no fault of the authors but, rather, occur because current NSF reporting structures lead to nonreporting of numbers that are deemed too small ($n < 10$) and because of a broader lack of representation of Indigenous scholars in academia.

Indigenous exclusion from NSF data is disheartening but not surprising. Implicit biases, stereotypes, and the overall invisibility of Indigenous Peoples in U.S. popular culture—together with explicit policies—influence how and even *whether* we are represented in data.

Invisibility in data, in turn, negatively affects the material support that Native communities receive. Moreover, such invisibility is dehumanizing and frequently prevents Native communities from having a seat at the table when important decisions that affect

Implicit biases, stereotypes, and the overall invisibility of Indigenous Peoples in U.S. popular culture—together with explicit policies—influence how and even *whether* we are represented in data.

these communities are made. For instance, when we see that our numbers are "too small to report," it can be easy for early-career researchers to ask, Do we even belong here at all? As a third-year Ph.D. candidate, I have asked myself this question many times. Often, it is only when I am in Indigenous spaces, such as at the American Indian Science and Engineering Society National Con-

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ference, that I find support and assurance that I can succeed in my field.

Eradicating systemic racism in academia *must* involve appropriate, accurate, and accessible data on Indigenous representation. Without accurate data about American Indian, Alaskan Native, Native Hawaiian, and Pacific Islander PIs, we cannot even begin to understand or mitigate the racial disparities that affect Indigenous groups.

Including Indigenous Communities

Data can both empower and marginalize groups, so it is necessary for institutions and individuals with privilege to assess how they are engaging with data, who they might be leaving out of conversations related to them, and why there are inequities in the first place. In their study, *Chen et al.* [2022] note that data for American Indian, Alaskan Native, Native Hawaiian, and Pacific Islander groups are routinely not reported, which complicates accurate calculations of funding rates. What does it say that a federal agency that plays a pivotal role in steering and implementing national research priorities leaves groups of people entirely out of its reporting on where funding is going (or not going)?

Invisibility of Indigenous Peoples is not a problem just within NSF funding data. Across disciplines, tribes are often left out of the planning and execution of research on Indigenous lands, and as a result, they may lack detailed information needed to make informed health decisions, for example, or access to data that can help with stewardship of natural resources across landscapes. As scientists shape and explore research questions around work on Indigenous lands, we must not leave out the communities from which this work is often derived.

Achieving representation within academic settings and research initiatives is a positive step but will not resolve issues of inequity without parallel shifts in the allocation of funding and resources. However, the current funding mechanisms that power academic institutions reinforce the same criteria that have characterized who has historically been most successful in those spaces: cisgender, heterosexual white males.

Achieving representation within academic settings and research initiatives is a positive step but will not resolve issues of inequity without parallel shifts in the allocation of funding and resources.

Chen et al. [2022] found that white PIs are funded by NSF at higher rates than any other racial group. This trend could result from biases in the selection process as well as from compounding disparities, such as education history and career longevity, between American Indian, Alaskan Native, Native Hawaiian, and Pacific Islander PIs and white PIs.

It's hard not to wonder whether any funded proposals by non-Indigenous researchers co-opt Indigenous data and knowledge to their benefit, especially as a means to enhance the stated broader impacts of their work. Is funding prioritized for those wishing to account for Traditional Ecological Knowledge or to work with tribal communities but not for Indigenous researchers themselves?

It is important to acknowledge how Indigenous Knowledge systems are increasingly being recognized as relevant across all disciplines, but we also must make sure that researchers are not benefiting from that knowledge in extractive or harmful ways. Indigenous communities maintain Ancestral Knowledges, which contributes to the greater body of knowledge helping us all understand Earth and environmental sciences. Excluding Indigenous populations, both from funding and by not acknowledging existing Ancestral Knowledges, limits the growth of this understanding. *Who* is getting funded to do work that engages Indigenous communities matters.

Ending Indigenous Erasure

Indigenous Peoples have resisted colonial, racist, and inequitable processes that have worked for hundreds of years to dispossess communities of their land and Traditional Knowledges. The resilience to persist against these systemic barriers is not new to us, and we will keep pushing against them.

In addition, entities can prove their allyship by helping to remove such barriers and ensuring that they aren't created in the first place. For agencies and institutions like NSF, this allyship can start with accurate and complete reporting of data. Such organizations can and should do better than to perpetuate the harmful myth that the numbers of Indigenous Peoples are too small to matter.

Specific recommendations for moving forward include the following:

1. Track trends for all groups regardless of the size of the data set. In its 2019–2020 Biennial Report to Congress, the Committee on Equal Opportunities in Science and Engineering, an advisory committee to NSF, highlighted a point made by *Wullert et al.* [2019]: "Small numbers cannot be a rationale to stall progress. Concluding that little can be said with limited data renders underrepresented groups more invisible and creates a roadblock to meaningful changes. To create lasting and impactful changes, organizations should be willing to analyze small numbers…and hold themselves accountable to making small numbers grow."

Rather than leaving out groups entirely, NSF should consider devising small-number statistical methods to analyze changes in funding accurately for these groups and report raw numbers.

2. Adopt the tenets of Indigenous data sovereignty and CARE principles. Indigenous data sovereignty affirms the rights of Indigenous Peoples to determine the means of collection, access, analysis, interpretation, management, dissemination, and reuse of data [*Kukutai and Taylor*, 2016]. This sovereignty derives from the inherent rights of self-determination as set forth in the United Nations Declaration on the Rights of Indigenous Peoples and mandates that data be used to support and enhance Indigenous Peoples' collective well-being. The CARE principles similarly seek to ensure Collective benefit, Authority to control, Responsibility, and Ethics regarding the use of Indigenous data [*Carroll et al.*, 2020]. NSF, other funding agencies, and individual scientists should incorporate Indigenous data sovereignty and CARE principles into project evaluations.

3. Include Indigenous experts in assessments of projects related to Indigenous Knowledges. If a funding proposal includes the use or analysis of Indigenous data, knowledge, or lands, Indigenous experts should be involved in assessing that proposal. Funding agencies could convene panels of cultural experts or community members to assess these types of proposals properly. These individuals should be compensated appropriately for contributing their time and knowledge.

4. Increase the number of awards available to underrepresented groups to bridge funding gaps. This recommendation echoes the point made by *Chen et al.* [2022] that the number of awards needed to bridge some racial disparities is small, and those disparities might be overcome with targeted programs for those groups. For work that engages Indigenous communities, the additional considerations of Indigenous data sovereignty and the use of Indigenous lands and Traditional Ecological Knowledge should be addressed by, for example, implementing CARE principles or including Indigenous experts on review panels as mentioned above.

Indigenous Peoples have been expert data collectors and keepers for thousands of years. We recognize the value of data, and we most definitely notice when our stories are absent from reported data. These facts will remain true regardless of power structures that try to make it otherwise. Through our own persistent efforts and those of allied individuals and institutions, however, we can continue changing these power structures to stop Indigenous erasure, in funding data and beyond.

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By **McKalee Steen** (mckalee_steen@berkeley.edu), a member of the Cherokee Nation and a doctoral student at the University of California, Berkeley

WMO WEATHERED THE COLD WAR, BUT CAN IT SURVIVE CAPITALISM?

AFTER 150 YEARS OF INTERNATIONAL COOPERATION, METEOROLOGY'S "VAST MACHINE" IS ADAPTING TO PRIVATE WEATHER FORECASTING.

BY BILL MORRIS

Clockwise from left: Yurii Bershadskiy via World Meteorological Organization/Flickr; World Meteorological Organization/Flickr; Emili Vilamala via World Meteorological Organization/Flickr; Yurii Bershadskiy via World Meteorological Organization/Flickr; Rodolfo Romeor via World Meteorological Organization/Flickr; Emili Vilamala via World Meteorological Organization/Flickr; World Meteorological Organization/Flickr; Jaegyu Yeo via World Meteorological Organization/Flickr; Šime Barešić via World Meteorological Organization/Flickr; Shukria Rezaie via World Meteorological Organization/Flickr; Torbjorn Toby Jorgensen/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

In winter 2018, a research team of which I was a part was tasked with an unusual mission: a shipwreck recovery. An uncrewed sailing vessel had been disabled in a storm off Cape Horn and drifted thousands of kilometers before washing up on the Auckland Islands, a remote archipelago south of New Zealand.

Along with thousands of ocean buoys, land-based weather stations, weather balloons, and a rapidly growing fleet of satellites, the shipwrecked saildrone (which was ultimately fixed and put back into service) was part of the huge network of devices that observe the world's atmosphere, land, and ocean—the "vast machine" that Victorian-era writer John Ruskin predicted would one day enable us to forecast weather.

The torrents of data this network collects are processed by powerful computers to create weather models. Meteorologists apply their expertise and experience to these models to make weather forecasts. Data, models, and forecasts are shared among countries and made available to anyone. It's a global system of free exchange that has prospered for 150 years.

At the heart of this vast machine is the World Meteorological Organization (WMO), an intergovernmental community whose primary role is to facilitate the free and open exchange of weather data for the benefit of all humanity.

For a century and a half, WMO has been an exemplar of international cooperation. It needs to be—weather respects no borders and affects everyone on Earth. But other forces, both economic and political, surround around WMO. At a time when we perhaps need it more than ever, WMO faces big questions about its future.

"Weather is a truly global phenomenon. In order to forecast, you can't just know the weather in your particular country—you need to know it globally."

FROM IMO TO WMO

"Weather is a truly global phenomenon," said Randy Cerveny, a climatologist with Arizona State University and a WMO historian. "In order to forecast, you can't just know the weather in your particular country—you need to know it globally."

That knowledge requires a standardized system of measurements. With this in mind, meteorologists from a number of countries set up the International Meteorological Organization (IMO) in 1876.

"It's an organization that was way ahead of its time," said Cerveny. "It started out as such a basic idea—that a temperature measured in New Zealand should be taken under the same set of conditions, and with the same type of instruments, as in the United States or Great Britain."

Such standards "seem like really simple things, but they're hard to get agreement on," said Paul Edwards, author of *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*.

From the start, sharing data to improve weather forecasts was fundamental to IMO's success. Among its early achievements was the first International Polar Year (1882–1883), a coordinated study of meteorology in the high latitudes.

"The unique thing about meteorology as a science is that it's dependent on data from a very large area," said Edwards. "Everybody has an incentive to participate. It's kind of like the postal service. It's better for everyone if they let the mail cross the border."

IMO was reorganized in 1950 as the World Meteorological Organization, an agency of the United Nations (UN). WMO was to act as UN's voice on atmospheric issues and the impacts of weather and climate.

COOPERATION, THE COLD WAR, AND CLIMATE CHANGE

In the postwar period, it was governments, rather than meteorological services, that sent representatives to WMO. The organization became not just a scientific gathering but also a diplomatic one.

One of WMO's early key roles was helping newly independent nations in Africa and elsewhere establish their scientific and technical capability. "There [was] a lot of effort poured into sending envoys to these new nations and helping them get set up," said Edwards, "which is in the interest of everyone, because it means the weather data continue to flow."

"The United Nations had to struggle with the postcolonial moment to maintain its legitimacy," said Joshua Howe, author of *Behind the Curve: Science and the Politics of Global Warming*. "One way to do that was through scientific development and knowledge-sharing programs.

"The WMO was a clear example of that. [It could] come in, build new infrastructure, coordinate existing infrastructure, and essentially give postcolonial nations in places such as Africa and Latin America a seat at the table."

The 1950's saw growing tensions between the United States and the Soviet Union. Cold War hostilities colored efforts such as the International Geophysical Year of 1957–1958, a global push to study Earth and its atmosphere.

"The whole program revolved around scientific cooperation and information sharing," said Howe. "But every part of it was also about competition between the U.S. and the Soviets for scientific preeminence."

One of WMO's landmark achievements during this time was the establishment of the World Weather Watch (WWW), a coordinated program of satellites and ground- and sea-based observing platforms that enabled the reach of forecasts to become, for the first time, truly global.

"They [got] that going long before the Internet, or any kind of computer networking in the sense we understand it today," said Edwards. "A lot of the value that the WMO [added was] by creating techniques for sharing data—by fax and by telegraph, across really large areas—and then establishing data centers that will receive data from a region and rebroadcast [those] data to other regions."

The development of WWW, said Andrew Blum, author of *The Weather Machine: A Journey Inside the Forecast*, was "very much in keeping with the American technological push, the Space Race, and this period of incredible advancement where suddenly you have a new vision of how the world can be interconnected."

"[It] was about creating a new scientific world according to American terms," Blum said, which, against the backdrop of Cold War tensions, "[was] totally about using technology to extend influence."

The U.S. dominance of WMO suggests a concerted effort to keep communism at bay. "The U.S. had a big stake in the UN in general," said Howe, "as a way to shore up the Western free market nations as a bloc to counter Soviet power."

But despite tensions between the United States and the Soviet Union, "international meteorology thrived in the Cold War," said John Zillman, former director of Australia's Bureau of Meteorology and WMO president from 1994 to 2003. "The U.S. and U.S.S.R. concluded it would be in everybody's global interest to find an area of cooperation. They focused on the use of space to improve warning of natural disasters."

There are, after all, major economic benefits to all nations in cooperating on weather forecasting.

"Weather forecasting has enormous economic value," said Edwards. "We get 25–50 times what we put into it back [from] farmers knowing something about what's going to happen to their crops, transport of all kinds, air travel, shipping, and a million other things that are weather dependent."

Because WMO is an international organization, inevitably agreement has been hard-won at times. "The price you pay for consensus," said Zillman, "is often fairly ambiguous wording in a global decision, so that everybody can live with it.

"But on the other hand…rarely does the international meteorological community seek anything other than a mutually beneficial outcome. I can't, in 30 years in the WMO, recall any real situation where we didn't have everybody's best interests in mind."

By the 1970s, for instance, it was apparent that long-term weather patterns were shifting, and it was universally beneficial to address the issue. WMO, along with the United Nations Environment Programme, set up the Intergovernmental Panel on Climate Change (IPCC) in 1988. Two decades later, with climate change recognized as the defining issue of our time, IPCC was awarded the Nobel Peace Prize.

RESOLUTION 40

WMO may have faced its greatest challenge in the 1980s, as market-oriented, conservative governments, especially the United Kingdom and the United States, put pressure on their meteorological services to recoup some of the considerable costs of gathering weather data by charging for them. This pressure coincided with the rise of private forecasting services like AccuWeather and the Weather Channel, which package government weather data for popular consumption on apps, television, and websites.

Neil Gordon was New Zealand's representative to WMO during this period. "What was happening," he said, "was observations from, say, France were going on international circuits into the United States to be used and ingested into weather models.… [Those data] would then go to companies like AccuWeather, who would then provide services back into France. And France was very unhappy about it. There was a risk that they would no longer send their data to the States."

"We almost got to the point where data exchange was being shut off," Gordon recalled.

At the Twelfth World Meteorological Congress, in 1995, urgent talk of data wars swirled. Without the free and open exchange of observational data, critics argued, the integrity and quality of global weather forecasts might be compromised. Some even feared that the ideological conflict could lead to the collapse of WMO itself.

Meetings ran late into the night as members tried to reach consensus. "The first 2 weeks were extremely tense," recalled Zillman. "Everybody was on edge."

Finally, a draft resolution was hammered out, encouraging WMO's continued commitment to making essential meteorological data and products freely available, recognizing that such data "are necessary for the provision of services in support of the protection of life and property and the well-being of all nations." When the resolution was brought before the WMO congress, "the atmosphere," Zillman wrote, "was electric."

Ultimately, Resolution 40 passed, to thunderous applause. "It was one of those times," recalled Zillman, "when grown men and women almost became like children, they were so relieved."

For the next 2 decades, Resolution 40 remained sacrosanct. "The WMO community that negotiated it got such a fright at the prospect of the collapse of international cooperation that they pretty much resolved not to touch it," said Zillman.

EARTH SYSTEMS

Today WMO has 193 members, with only 10 UN member states (mostly tiny islands and microstates lacking their own meteorological services) not part of it. Even countries the United States considers state sponsors of terrorism, including Iran and North Korea, are members.

Blum, who attended the WMO congress in 2015, said a strong American influence is still a big part of the organization's DNA. "I was probably naive about this going in, but I hadn't quite realized the extent to which the U.S. was the 800-pound gorilla in the room," he said.

WMO's core budget is funded mostly by member contributions, which are adjusted according to each member's ability to pay. In 2021, contributions from members totaled nearly $74 million.

> **"I can't, in 30 years in the WMO, recall any real situation where we didn't have everybody's best interests in mind."**

Alongside the distribution of weather data, WMO's mission includes addressing such concerns as the monitoring of greenhouse gas emissions, disaster prevention, and access to fresh water.

"The WMO has gone well beyond its initial mission of collecting and collating temperature and humidity [data]," said Howe. "They're involved in all kinds of programs that have helped us map and understand the changing climate."

A big shift in recent years, said current secretary-general Petteri Taalas, has been movement toward a holistic view of Earth processes. "Instead of talking about meteorology, hydrology, and oceans as separate things," he said, "it very much makes sense to talk about 'Earth systems.'"

Monitoring these is the job of WMO's Global Observing System (GOS). GOS includes orbiting and geostationary satellites, aircraft, ocean buoys, dedicated marine and freshwater vessels, radar networks, weather stations, and lots and lots of data processing and management.

As vast as GOS is, there are still blind spots. “We have major gaps...in African countries, Caribbean islands, and also the Pacific islands,” said Taalas.

Filling in these gaps is a big part of WMO’s current focus. Another is establishing and improving early-warning systems around the globe, which, it is hoped, will save thousands of lives from being lost to extreme weather events .

“We always say weather and climate and water know no boundaries. We have to cooperate.”

In the next few years, WMO aims to convince governments and other funding agencies to direct almost $3.5 billion toward upgrading weather forecasting services, especially in the most at-risk areas. Planned infrastructure including early-warning systems and enhanced meteorological systems in places like Afghanistan and West Africa is “a very powerful way to adapt to climate change,” said Taalas. “At the moment, only half our members have state-of-the-art weather services.”

Bapon Fakhruddin is a water management specialist and risk assessor with the United Nations’ Green Climate Fund. He has designed climate and disaster response projects in Africa, Asia, the Caribbean, and the Pacific, where he helps remote island nations prepare for increasingly severe weather events.

“Places like Tokelau, Tuvalu, and Kiribati are highly vulnerable,” he said. “Many of those countries don’t have skilled manpower that can generate their own forecasting on a local scale, and when you’re looking at severe weather forecasting, it needs to be very localized.”

Small island developing states (SIDS) typically rely on forecasting services from bigger neighbors, which might be hundreds, even thousands, of kilometers away. Developing robust early-warning systems requires training staff in SIDS to build accurate local forecasts. These systems also allow countries to plan for the aftermath of a severe weather event.

Developing nations, Fakhruddin explained, usually have low capacity to bounce back from extreme weather events, “so it’s very urgent; we need to take action rapidly to help these countries.”

This, he said, is where WMO, with its globally coordinated approach, comes in. “Their job is to enhance policy, identify the gaps, and investigate how they could find [financing] to help those countries.”

Sharing data is fundamental to creating effective early-warning systems. Weather information gathered via GOS is made available to members through WMO’s Global Telecommunication System (GTS).

Australian meteorologist Sue Barrell, former vice president of the WMO Commission for Basic Systems, said the weather and climate models WMO produces “are now so well tuned to using all of the data they can get, that when some data [aren’t] available, that actually impacts the forecasts on the other side of the world. If [for example] New Zealand chose not to share its data, the weather forecasts in the United States would be poorer.”

Recently, Russia’s invasion of Ukraine has tested this culture of sharing. Russia has ceased to supply many of its weather data sets to WMO, and some European agencies have responded in kind. “So-called ‘essential’ data [are] still freely exchanged,” said Taalas, “but there are many nonessential data sets that are no longer exchanged. For example, Russia stopped delivery of weather radar data, which [are] used for short-term rainfall monitoring, 2 weeks before they started to attack Ukraine.”

Nonetheless, a Russian Federation delegate attended WMO’s 2023 Executive Council meeting in February. “We’re not a political organization,” said WMO media officer Clare Nullis. “We’re a scientific and technical organization. We always say weather and climate and water know no boundaries. We have to cooperate.”

Indeed, the chief challenge to WMO’s spirit of cooperation is not overtly political at all: In the Internet era, weather forecasting is big business.

PUBLIC-PRIVATE PARTNERSHIPS

“I used to joke that the Internet was invented for meteorologists,” said Russ Murley, operations manager with Maine-based Precision Weather, one of North America’s oldest private forecasting companies.

Precision Weather takes data from the Internet, gathered mostly from government sources, and runs them through its in-house computer modeling systems to create weather forecasts specific to very localized areas.

The addition of technologies like drones, home weather stations, and even smartphones allows companies like Precision to create and sell forecasts that are more accurate, at the local scale, than those supplied by the government. Among other things, Precision Weather provides tailor-made forecasting for New York’s subway system and has forecasted for events ranging from the Golden Globe Awards to actor Reese Witherspoon’s wedding.

In recent years, said Murley, private weather forecasting has risen exponentially.

It’s driven by demand: Insurance companies want to know the potential damages associated with a tropical storm long before it makes landfall, for instance. Cities want to prepare municipal services for localized snow events. Department store chains want to know whether to stock more paddling pools or puffer jackets.

At the same time, the advent of small, relatively low cost satellites and the increased availability of computers powerful enough to process the data mean that private satellite firms can now compete directly with governments to make observations and forecasts of Earth’s weather.

One such company is San Francisco–based Spire, which operates a constellation of more than a hundred satellites, each the size of a loaf of bread. Spire uses the data it collects to create its own weather models, which it says greatly increase global weather forecasting capability.

“We have unique data going into our model that other people don’t have,” said Michael Eilts, Spire’s general manager of weather and Earth intelligence.

“In data-rich areas, like over the continental United States or Australia, we probably don’t add as much value, but when you get over the open oceans, where there are very [few] other data sources, we do have a distinct advantage in our forecast capability,” Eilts added.

This capability comes as the effects of global climate change are starting to bite. “As weather becomes more extreme,” said Blum, “there’s more to gain by predicting weather, and more value in those predictions.”

WMO, an agency of the United Nations, is headquartered in Geneva. Credit: Torbjorn Toby Jorgensen/Flickr, CC BY-SA 2.0 (bit.ly/ccbyncsa2-0)

Although the rise of private weather forecasting may in some ways seem to threaten the value of WMO, the industry may also contribute to the organization, supporters say. The detailed, highly accurate data gathered by private companies can be combined with government data to provide more reliable models and forecasts. NOAA, for instance, now partners with a number of private weather data firms.

"What we've come to understand," said John Cortinas, director of NOAA's Atlantic Oceanographic and Meteorological Laboratory in Miami, "is that by working together, we can make more progress collectively than we would be able to individually.... There are new technologies that the private sector has developed in a much more rapid way than traditionally we've been able to do on the federal government side."

Saildrone, for example, the company that owns the uncrewed vessel that foundered on the Auckland Islands in 2018, charters its vessels to NOAA to study hurricanes forming in the Atlantic Ocean and Caribbean Sea. On two occasions, it sent drones into the middle of tropical storms, gathering never-before-available data and video that NOAA hopes will aid in forecasting hurricanes.

The data the drones collect end up on the GTS for the world to access. "That's a perfect example of how that synergy worked well, to everyone's benefit," Cortinas said.

Since 2016, Spire has been selling its satellite data to NOAA, fulfilling contracts valued at $23.6 million in 2022. Eilts said the data are analyzed by both NOAA and Spire's own scientists to improve modeling capability. "It's a community effort. In the end, though, government forecasts are far better because of the data that we sell to them."

But access to the high-tech world of commercial weather forecasting comes with a trade-off: Private satellite data often have restrictions on how and when they can be shared.

"We need to continually find ways to maximize the value out of the data that we collect," said Eilts. "What's happened so far is that NOAA has funded us...to share [Spire's] data with researchers, but they can't hand [those] data off to our commercial competitors.

"So that's the game that we're playing right now. We're happy to sell [data] to governments. And if they want to pay a little extra so they can share [them] with a broader community, great. But we won't let [them] become just open to the public so that other commercial companies can take our data and compete against us."

Such restrictions in many ways run counter to WMO's traditional "free and open" data-sharing policies, but the organization has no power to compel a private company to make data available for sharing.

"The whole system has evolved into a public-private partnership, and nobody is particularly running the show," said Edwards. "The WMO can urge and cajole, but it can't make any organization or country do anything."

"You can't have the spoils of Silicon Valley without giving them their pound of flesh," said Blum. "We want [those] additional data, even if it means breaking some of the 150-year-old culture of data exchange."

The price of data produced by such companies may put them out of reach of some governments—including, perhaps, those of countries at the greatest risk from climate change.

"The whole system has evolved into a public-private partnership, and nobody is particularly running the show."

"In theory," said Taalas, "we could have a situation where the richest countries could pay for the data and poor countries wouldn't be able to do so."

Barrell agreed that meteorological services, especially those from smaller member states, are being increasingly challenged. "A government would say, 'Why do we need to invest in a met service when we can go to [the Internet] and get everything we need?' What you lose then," she explained, "is the investment in the long-term climate record, and the long-term skills and depth that a national meteorological service has."

Between 2019 and 2021, in response to these pressures, Barrell led a WMO task force that for the first time in 2 decades, reassessed Resolution 40. "Resolution 40 was quite revolutionary at the time," she said. But, echoing what Zillman noted earlier about the pitfalls of "fairly ambiguous wording" in international agreements, Barrell said the "essential meteorological data" mentioned in Resolution 40 were never specified. "Its weakness was that it didn't actually articulate what [data] needed to be shared. It created some ambiguity."

To address this, the task force developed the Unified Data Policy. The policy identifies "core data," which, Barrell said, "[are] to be shared freely, without any restrictions at all," and "recommended data, " which WMO encourages members to share.

Core data include observations of surface atmospheric pressure, air temperature, and humidity that are deemed necessary "for the provision of services in support of the protection of life and property and for the well-being of all nations."

Recommended data, which might include data gathered by regional weather stations, are "pretty much everything else," Barrell said. "People can charge for [those] data, or they can put conditions on [their] use."

"There's also an element in [the Unified Data Policy] that says when there's a weather disaster [like] a cyclone or other major event, we call on everyone to share their data freely," Barrell said. "So that is a call to the private sector. It's not written in law—it's a moral obligation for them to be part of that community."

WMO IN A MULTILATERAL WORLD

When it comes to building early-warning systems, Fakhruddin, for one, is a strong advocate for creating favorable commercial environments to attract private forecasting services to at-risk areas like the Pacific. "When [countries] don't have an observation network, [private] satellite data would help them an enormous amount," he said.

Finding the estimated $3.5 billion needed to provide "early-warning systems for all," he said, will not be easy. "No one global agency has that kind of money. So your best bet is how you can bring private money into the sector."

Barrell said finding a path in which private and public interests work together will ultimately benefit everyone. "Will it work perfectly? No, nothing ever does. But I think the signs are there that the major parties involved can see the benefit."

Zillman said he believes that the fundamental WMO ethos, which has survived for a century and a half, will ultimately ride out the storm.

"There will always be a very large public good component in international meteorology," he said. "I think it's entirely central to the WMO's role to help keep the global weather enterprise working in the interests of both the public and private sectors."

The bigger challenge WMO faces, said Howe, is redefining itself in a world very different from the one into which it was birthed. The Cold War rivalry that fueled the technological race upon which WMO built its legacy is a thing of the past. And while most countries, including China, embrace WMO philosophies, questions remain over the role the organization will play in world affairs.

"I don't believe that private satellites are an existential threat for the WMO," said Howe. "They've comprised a part of what the WMO has done."

"More profoundly," he continued, "I think the retraction from international governance structures within the international political economy is a more severe threat. The United Nations doesn't have the credibility it once did. It's not a centerpiece of global governance in the way that it hoped to be at one point. Even the IPCC has kind of run its course.

"It's not an existential threat. It's a relevance threat."

And yet, despite the shifting political landscape, weather will always remain a global issue. A 2021 World Bank report concluded that improving global weather observation capability could result in socioeconomic benefits exceeding $5 billion a year. This pressing need, perhaps more than anything, is what will keep WMO intact.

"Every country that's [been a part of WMO]," said Edwards, "has ended up saying, 'This is a benefit, and we want to get as much as we can out of it.' So it just has this kind of inherent planetary dimension."

And in the face of climate change, it could be argued that the world needs WMO more than ever.

"There's so much that we can share," said Barrell, "in terms of adaptation, in terms of modeling, and in terms of informing policy. It really is a global community. It has to be a global solution."

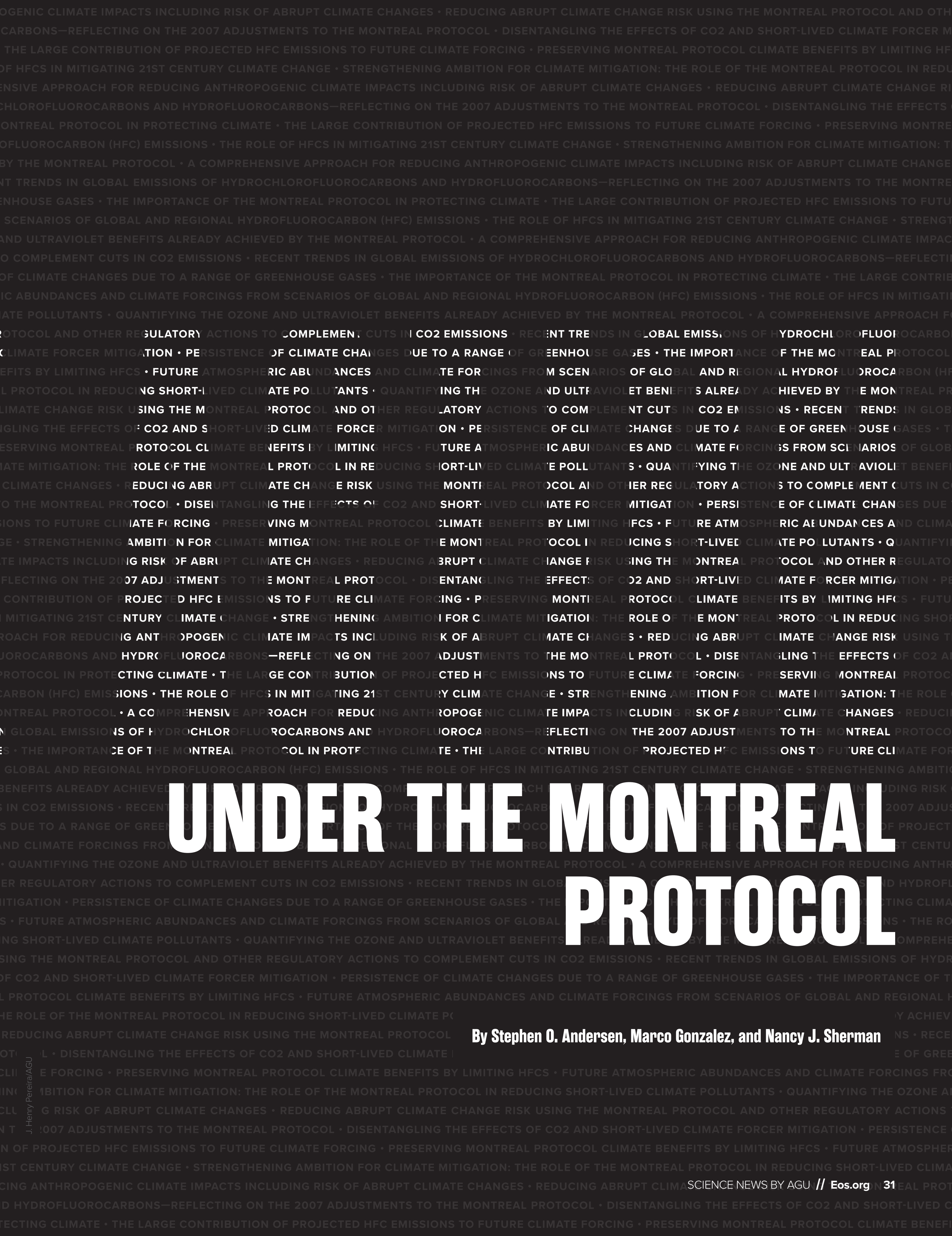
AUTHOR INFORMATION

Bill Morris, Science Writer

Read the article at Eos.org

SETTING THE STAGE FOR

Twelve papers formed the scientific basis for the Kigali Amendment, which strengthened the landmark treaty safeguarding atmospheric ozone.



J. Henry Pereira/AGU

UNDER THE MONTREAL PROTOCOL

By Stephen O. Andersen, Marco Gonzalez, and Nancy J. Sherman

In 1974, chemists Mario J. Molina and F. Sherwood Rowland warned that chlorofluorocarbons (CFCs), compounds widely used at the time as refrigerants and aerosol propellants, could destroy the stratospheric ozone layer [*Molina and Rowland*, 1974]. This layer protects Earth's surface from harmful ultraviolet (UV) radiation that, in excess, can cause skin cancer and cataracts, suppress the human immune system, damage crops and natural ecosystems, and degrade the built environment. The following year, atmospheric scientist Veerabhadran Ramanathan further warned that CFCs and other chlorinated fluorocarbons are also powerful greenhouse gases [*Ramanathan*, 1975].

In the ensuing decade, scientists measured and documented the buildup and long lifetimes in the atmosphere of CFCs and other ozone-depleting substances (ODSs). They also provided theoretical proof that ODSs chemically decompose in the stratosphere and catalytically deplete stratospheric ozone, and they quantified the adverse health, environmental, and economic effects of CFCs.

Warnings that ozone depletion from CFCs could increase the incidence of skin cancer sparked consumer boycotts of products made with and containing ODSs, such as aerosols and certain polystyrene foam food service containers. The boycotts then expanded into government prohibitions of specified products.

Reports that CFCs also acted as greenhouse gases sparked scientific investigations into what substances besides carbon dioxide (CO_2) might destabilize the atmosphere and how the evolving cocktail of climate pollutants could be considered.

The scientific evidence was enough for the executive director of the United Nations Environment Programme, Mostafa K. Tolba, to persuade 25 countries and the European Union to sign the Vienna Convention for the Protection of the Ozone Layer in March 1985, setting the stage for international controls on ODSs [*Benedick*, 1998; *Andersen and Sarma*, 2002; *Tolba and Rummel-Bulska*, 2008].

Less than 2 months later, Joseph Farman and colleagues provided observational evidence of a stratospheric "ozone hole" over the Antarctic potentially linked to rising CFC concentrations [*Farman et al.*, 1985], which ultimately led to international agreement on the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, better known simply as the Montreal Protocol.

Twenty years later, every United Nations (UN) member state had become a party to the Montreal Protocol, more than 99% of ODS production and consumption worldwide had been phased out, and the ozone layer was well on its way to recovery [*World Meteorological Organization* (*WMO*), 2018; *Ajavon et al.*, 2015]. Accomplishments like these inspired former secretary-general of the United Nations Kofi Annan to state that the Montreal Protocol was "perhaps the single most successful international agreement to date" [*Hunter et al.*, 2022].

As it has turned out, the protocol not only has been enormously successful in curtailing the depletion of stratospheric ozone but also has taken on a second life in recent years as a de facto—and highly beneficial—climate treaty. The protocol's achievements in both respects hold valuable lessons for future climate- and environment-focused policymaking efforts.

The Montreal Protocol has taken on a second life in recent years as a de facto—and highly beneficial—climate treaty.

To better understand and apply these lessons in the future, it's worthwhile to parse the science that went into formulating the Montreal Protocol and led to its transformation into a climate treaty.

From an Ozone Treaty to a Climate Treaty

The Montreal Protocol is described as a "start and strengthen" treaty, because after initially imposing controls on just two classes of chemicals (CFCs and halons), it was subsequently strengthened by amendments, which require ratification by a certain number of parties, and by adjustments, which require just the consensus of all parties.

Four amendments in the 1990s were crafted during meetings in London (1990), Copenhagen (1992), Montreal (1997), and Beijing (1999). These strengthened the treaty by adding additional ODSs to the list of those controlled. Six adjustments were agreed upon in London (1990), Copenhagen (1992), Vienna (1995), Montreal (1997), Beijing (1999), and Montreal (2007)—further strengthening the treaty by transitioning ODS phasedowns to phaseouts and then by accelerating those phaseouts.

The transition of the Montreal Protocol from a stratospheric ozone protection treaty to a climate treaty began in 2007. This is when atmospheric and climate scientist Guus J. M. Velders and colleagues, after analyzing historical and potential future ODS emissions, reported that the Montreal Protocol and its phaseout of ODSs had done more to reduce greenhouse forcing and mitigate climate change than any other treaty, including the Kyoto Protocol [*Velders et al.*, 2007].

That same year, the protocol's usefulness in further protecting climate inspired parties to approve an acceleration of the ongoing hydrochlorofluorocarbon (HCFC) phaseout, which had started with the 1999 Beijing Amendment.

The transition to a climate treaty continued for 9 more years, culminating with the fifth Montreal Protocol Amendment (2016 Kigali Amendment) controlling hydrofluorocarbons (HFCs), which are safe for stratospheric ozone but are strong greenhouse gases. Markets for HFCs had grown rapidly, and they had come into widespread use as necessary replacements for some CFCs, allowing the rapid phaseout of ODSs, but in some cases, HFCs trap thousands of times more heat than CO_2 [*WMO*, 2018; *Zaelke et al.*, 2018; *Hunter et al.*, 2022].

Signatories of the Kigali Amendment, named for the capital city of Rwanda, are phasing down HFCs. The amendment also encourages greater energy efficiency in next-generation equipment and the use of alternate chemicals to replace HFCs in applications such as air-conditioning, refrigeration, and thermal insulating foam.

Timelines for initial HFC consumption and production freezes (i.e., no further increases in consumption and production are allowed) and phasedowns are ambitious. Yet parties took a leap of faith, consistent with the precautionary principle, that alternatives to HFCs would be available and affordable. (Substitutes are indeed now available in most applications. Many also offer higher energy efficiency than HFCs [*Technology and Economic Assessment Panel*, 2021].)

For most developing countries, the freeze begins in 2024, and phasedown begins in 2029, whereas for "high ambient temperature" countries, the freeze begins in 2029 and phasedown begins in 2032. The timeline for developed countries was even more aggressive, with the phasedown intended to begin in 2019 for most parties and in 2020 for the Russian Federation and a few other countries of the former Soviet Union. In the United States, which recently ratified the Kigali

Attendees of the 28th Meeting of the Parties to the Montreal Protocol in Kigali, Rwanda, where the Kigali Amendment was reached, listen to a panel discussion on 13 October 2016. Credit: Rwanda Environment Management Authority/Flickr, CC BY-ND 2.0 (bit.ly/ccbynd2-0)

Amendment, a plan to reduce HFC use was codified in late 2020 with the passage of the American Innovation and Manufacturing Act.

Ultimately, the dangers to society, economies, agriculture, and public health posed by expected climate change and the links between this change and the continued use of HFCs convinced parties to the Montreal Protocol that fast action was necessary. These links were spelled out clearly in a series of scientific studies carried out from 2007 to 2016.

Twelve Papers That Justified Phasing Down HFCs

In consultation with scientists and other colleagues, we set out to identify core scientific papers published either during deliberations for the 2007 adjustment that accelerated the phaseout of HCFCs or for the 2016 Kigali Amendment. The purpose was to recognize those who worked to understand the contributions of CFCs, HCFCs, and HFCs to climate change and to inform policymakers and the public. Demonstrating the important contribution of published scientific research to groundbreaking environmental policy may help inspire and motivate others to publish their own research and make it available to decisionmakers.

Although many quality studies have quantified and assessed the climate impacts of HFCs, here we highlight studies that were particularly influential in accelerating the HCFC phasedown and HFC phasedown. Specifically, we evaluated papers based on whether they were crafted to inform Montreal Protocol and other government policymakers; focused on quantifying the potential effects of HFC reductions on climate forcing (i.e., in equivalent CO_2 emissions); and written by authors, contributors, or reviewers of the 2014 and 2018 reports of the Montreal Protocol Scientific Assessment Panel (SAP), an advisory group composed of hundreds of international experts who periodically evaluate atmospheric ozone conditions and related issues.

From our evaluation, we identified 12 papers (see sidebar on p. 34) that formed the scientific foundation for the Montreal Protocol parties to take bold steps to phase down HFCs via the Kigali Amendment. These thoroughly researched and clearly presented scientific papers, which were among those contributing to SAP presentations at Meetings of the Parties and were directly read and considered by treaty negotiators from party countries, made the link between HFCs and climate change apparent and persuaded skeptics and stakeholders to take action. All told, the authors of these dozen papers include about 40 scientists from 10 countries, reflecting the substantial degree of international attention to the problems posed by HFCs and scientific collaboration to address them.

Other scholars of the Montreal Protocol may have different opinions about which studies were most significant in informing the Kigali Amendment or about what criteria should be applied in evaluating studies. We welcome such differences of opinion because they will spur discussions that help trace the evolution of scientific understanding and its links to policy resolve in this case—and perhaps offer useful insights in future cases.

Following their groundbreaking 2007 study showing the benefits to climate change mitigation of ODS drawdowns, Velders and the same group of colleagues published another prominent study in 2009. In it, they find that regulatory controls on ozone-safe HFC greenhouse gases could significantly reduce anthropogenic climate forcing even as CO_2 reductions are aggressively pursued for long-term success [*Velders et al.*, 2009]. For example, in a scenario in which HFC consumption levels are frozen and then gradually drawn down from 2013 to 2050, the global warming potential would be reduced by

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Chipperfield, M. P., et al. (2015), Quantifying the ozone and ultraviolet benefits already achieved by the Montreal Protocol, *Nat. Commun.*, *6*, 7233, https://doi.org/10.1038/ncomms8233.

Molina, M., and D. Zaelke (2013), *A Comprehensive Approach for Reducing Anthropogenic Climate Impacts Including Risk of Abrupt Climate Changes, Fate of Mountain Glaciers in the Anthropocene, Proceedings of the Working Group, 2-4 April 2011*, edited by P. J. Crutzen, L. Bengtsson, and V. Ramanathan, *Scripta Varia 118*, Pontifical Acad. of Sci., Vatican City, www.pas.va/content/dam/casinapioiv/pas/pdf-volumi/scripta-varia/sv118/sv118-molina-zaelke.pdf.

Molina, M., et al. (2009), Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions, *Proc. Natl. Acad. Sci. U. S. A., 106*, 20,616–20,621, https://doi.org/10.1073/pnas.0902568106.

Montzka, S. A., et al. (2015), Recent trends in global emissions of hydrochlorofluorocarbons and hydrofluorocarbons—Reflecting on the 2007 adjustments to the Montreal Protocol, *J. Phys. Chem. A, 119,* 4,439–4,449, https://doi.org/10.1021/jp5097376.

Rogelj, J., et al. (2014), Disentangling the effects of CO_2 and short-lived climate forcer mitigation, *Proc. Natl. Acad. Sci. U. S. A., 111*, 16,325–16,330, https://doi.org/10.1073/pnas.1415631111.

Solomon, S., et al. (2010), Persistence of climate changes due to a range of greenhouse gases, *Proc. Natl. Acad. Sci. U. S. A., 107*, 18,354–18,359, https://doi.org/10.1073/pnas.1006282107.

Velders, G. J. M., et al. (2007), The importance of the Montreal Protocol in protecting climate, *Proc. Natl. Acad. Sci. U. S. A., 104*, 4,814–4,819, https://doi.org/10.1073/pnas.0610328104.

Velders, G. J. M., et al. (2009), The large contribution of projected HFC emissions to future climate forcing, *Proc. Natl. Acad. Sci. U. S. A., 106*, 10,949–10,954, https://doi.org/10.1073/pnas.0902817106.

Velders, G. J. M., et al. (2012), Preserving Montreal Protocol climate benefits by limiting HFCs, *Science, 335*, 922–923, https://doi.org/10.1126/science.1216414.

Velders, G. J. M., et al. (2015), Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions, *Atmos. Environ., 123A*, 200–209, https://doi.org/10.1016/j.atmosenv.2015.10.071.

Xu, Y., et al. (2013), The role of HFCs in mitigating 21st century climate change, *Atmos. Chem. Phys., 13*, 6,083–6,089, https://doi.org/10.5194/acp-13-6083-2013.

Zaelke, D., S. O. Andersen, and N. Borgford-Parnell (2012), Strengthening ambition for climate mitigation: The role of the Montreal Protocol in reducing short-lived climate pollutants, *Rev. Eur. Compliance Int. Environ. Law*, 21(3), 231–242, https://doi.org/10.1111/reel.12010.

the equivalent of 106–171 gigatons of CO_2, and global radiative forcing would be reduced by 0.18–0.30 watt per square meter by 2050. This paper started the debate among Montreal Protocol parties that culminated in the 2016 Kigali Amendment.

Subsequently, more papers validated, extended, and enhanced these 2009 findings and were incorporated into Montreal Protocol SAP reports. We have identified 10 papers in addition to *Velders et al.* [2007, 2009] that provided primary warnings about hazards to environmental and human health from HFCs, clear elaboration of the emerging problem, and guidance about what must be done—and how fast—to avoid existential threats and catastrophic consequences.

For example, *Montzka et al.* [2015] reported that global atmospheric measurements of HFCs from 2007 to 2012 were consistent with modeled projections by *Velders et al.* [2009] but were twice as large as the amount of HFC emissions reported to the UN Framework Convention on Climate Change, likely reflecting the rapid growth in the use of these chemicals as substitutes for HCFCs, which were being phased out under the Montreal Protocol.

Earlier, *Solomon et al.* [2010] illustrated the complexity of atmospheric processes and showed how warming effects can extend beyond the time needed for greenhouse gases to degrade. These authors emphasized the need to act quickly to prevent long-lasting and heat-amplifying impacts, such as the transfer of heat to the oceans.

Turning Beneficial Science into Beneficial Policy

Science often informs major, environmentally beneficial policy shifts—think of the research that initiated efforts to draw down the use of hazardous pesticides or lead in gasoline—but rarely does it do so as rapidly as it did in the case of the Kigali Amendment. As we face many other ongoing Earth system and global health challenges, persuasive science will continue to be necessary to build the confidence of policymakers to act according to the precautionary principle, which requires action to avoid possibly irreversible effects long before all the scientific details of an issue are certain [*Willi et al.*, 2021].

The overarching lesson from the Kigali Amendment is that research, analysis, and publication by scientists focusing on current and emerging environmental threats are essential to successful and timely policy action to address them. As Sherwood Rowland said at a White House climate change roundtable in 1997, paraphrasing others before him, "If not us, who? If not now, when?"

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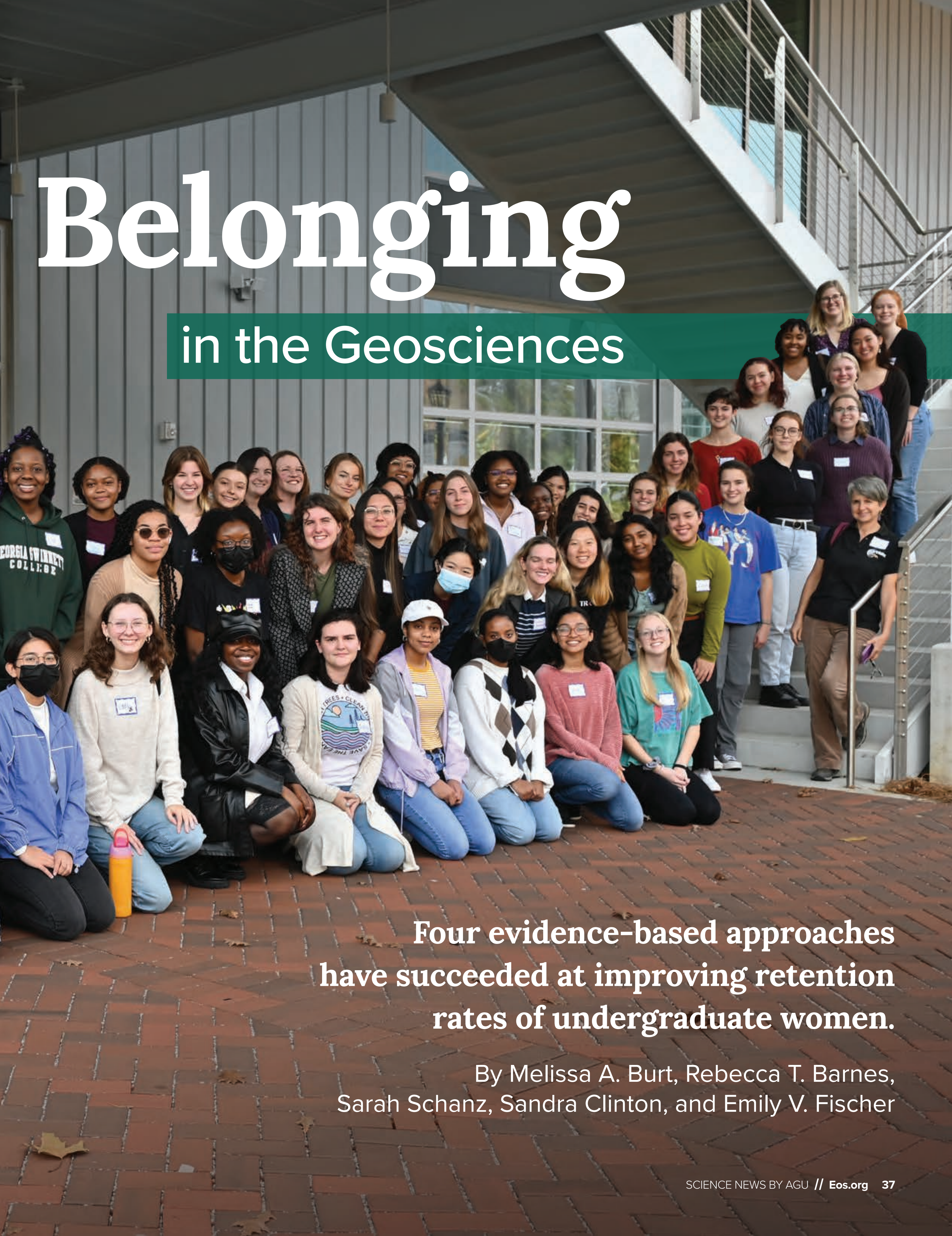
Mentorship Builds Inclusivity *and*

Participants and organizers in the PROGRESS (Promoting Geoscience Research, Education and Success) program gathered for a workshop in Atlanta, Ga., in fall 2022. Credit: Ivan Schustak



Belonging in the Geosciences

Four evidence-based approaches have succeeded at improving retention rates of undergraduate women.

By Melissa A. Burt, Rebecca T. Barnes, Sarah Schanz, Sandra Clinton, and Emily V. Fischer

People from marginalized communities who pursue degrees in science, technology, engineering, or mathematics (STEM) face obstacles such as hostile work environments (e.g., sexual harassment), lack of representation, and poor mentorship that challenge their sense of belonging [e.g., *Berhe et al.*, 2022]. This is true for Black, Indigenous, and Latinx/e people, as well as for other people of color, LGBTQIA+ people, white women, and people with disabilities. Efforts to diversify the STEM community and workforce have focused largely on recruitment while neglecting the work needed to retain individuals and ensure their sense of belonging [*Allen-Ramdial and Campbell*, 2014].

The geosciences are one of the least diverse fields within STEM. A lack of gender parity contributes to this problem. Such underrepresentation of women, especially those from racially and ethnically excluded groups, emerges at the undergraduate level in the geosciences.

In 2015, we created PROGRESS (Promoting Geoscience Research, Education and Success) as an experimental program serving 11 institutions in the Colorado-Wyoming Front Range and the Carolinas to develop, test, iterate, and scale strategies to support women's persistence in the geosciences. Since then, PROGRESS has expanded to three additional regions (around Atlanta; El Paso, Texas; and College Station, Texas) and 12 more institutions, including community colleges, undergraduate-only institutions, and larger research (i.e., R1) schools.

Our project recruits first- or second-year STEM undergraduates who identify as women. The goal is nurturing their interest in the geosciences through mentoring, introduction to role models, professional development opportunities, and online and in-person discussions and resources. Workshops are designed on the basis of published research and demonstrated approaches and are a core component of PROGRESS. These workshops connect undergraduate women with more senior mentors in the geosciences, establish connections among students on individual campuses and regionally, and expand students' ecosystems of support to help them gain technical and professional skills.

A panelist speaks with student participants during a workshop in Atlanta organized by the PROGRESS (Promoting Geoscience Research, Education and Success) program. Credit: Ivan Schustak

Exposure to role models helps to increase students' science identity, break down stereotypes of what scientists look like, and increase their sense of belonging.

As documented in several studies, PROGRESS has raised awareness and improved retention of undergraduate women in the field. Given this success, and the broadening acknowledgment of the many barriers to inclusion within the geosciences, we offer results and strategies of this program as a valuable model for other efforts aimed at diversifying and retaining women in STEM.

Below we summarize four critical elements for meaningfully supporting undergraduate women. These practices are not comprehensive. Rather, they are examples of ways to nurture and build a geosciences community that is supportive, inclusive, and equitable, and one that ultimately offers the opportunity for students to feel a greater sense of belonging.

Representation and Science Identity

Studies have found that undergraduate students who identify with science or as a "science person" are more likely to persist to graduation and perform well in science fields [*Chen et al.*, 2021]. Introducing undergraduate women to professionals with a variety of perspectives, backgrounds, and life paths provides students with opportunities to observe people like themselves succeeding. This exposure to role models helps to increase students' science identity, break down stereotypes of what scientists look like, and increase their sense of belonging [e.g., *Good et al.*, 2012].

Consistent with others' recommendations to highlight the relevance of scientific work and the varied paths to success in science careers, PROGRESS engages participants with an empowering 1-day workshop, where they are introduced to professionally and ethnically diverse women geoscientists through a series of panels. Panelists describe their individual career experiences, which emphasizes to the students the variety of entry points into the field and the multifaceted professional and personal pathways taken by successful geoscientists.

In a study of PROGRESS participants, students reported being inspired by relevant role models who had shared their pathways to achieving success. Those introductions to role models led to higher rates of persistence in geoscience fields among PROGRESS participants compared with students who did not participate in the program [*Hernandez et al.*, 2018]. In fact, on average, the likelihood of a PROGRESS student staying in the geosciences doubled with each additional same-gender role model they identified.

Early Engagement and Access to Resources

Many students have limited precollege exposure to the geosciences but are attracted to these fields as undergraduates because of a love of the outdoors, fond memories of familial experiences, or positive experiences in elective courses [*Holmes and O'Connell*, 2003]. Early engagement in STEM has been shown to increase student persistence and retention in these disciplines, particularly among historically excluded groups. Early engagement with students by geoscientists is thus important to increasing their awareness of, and retention within, the field.

In PROGRESS, students have reported, and program leaders have anecdotally observed, many benefits of early engagement with our program's activities. These benefits include increasing students' knowledge of and access to opportunities in the geosciences (e.g., undergraduate research experiences and tips for applying to them), helping them establish and broaden a support system in the field (e.g., through peer and local mentoring), and allowing them to explore and develop individual skills that are useful in the geosciences (e.g., strategies on how to navigate obstacles).

A student maps out a plan for developing a mentoring network, or ecosystem of support, at a PROGRESS workshop. Credit: Ivan Schustak

Many people perceive a lack of communal goals within STEM disciplines and have pointed to this as one reason for large gender disparities. We aim to dispel this myth.

The Societal Relevance of the Geosciences

Geoscience topics, knowledge, and expertise are central to many of the most challenging problems facing society today—from climate change and water security to air pollution and natural hazards—as well as to potential solutions to these challenges. Therefore, we need future scientists to be well versed in Earth system processes and interdisciplinary approaches.

Studies have suggested, however, that many people perceive a lack of communal goals (i.e., goals oriented toward working with or helping others) within STEM disciplines and have pointed to this as one reason for the large gender disparities [e.g., *Diekman et al.*, 2017].

In PROGRESS workshops, we aim to dispel this myth by helping participants understand the societal relevance and collaborative nature of the geosciences. For example, we introduce various geoscience fields paired with global challenges that scientists in these fields are helping to address, such as atmospheric scientists and air pollution, seismologists and natural disasters, and hydrologists and water quality. These approaches help defuse conflicts that students may experience between their personal and professional goals. They also promote stronger intentions to continue in the field, as we documented in a recent study [*Henderson et al.*, 2022].

Communities of Support

Students are often under the impression that they need only one mentor, not recognizing the many benefits of having multiple mentors. As several studies have illustrated, a multitiered, multimentor

It is critical that we collectively increase our community's valuation of and capacity for mentorship.

approach is more beneficial to mentees, not only providing them with multiple perspectives but also helping build their networks and increasing their sense of belonging [e.g., *Pandya et al.*, 2007].

PROGRESS stresses the importance of developing an ecosystem of support that can provide a mentee with intellectual, career, and wellness support. Specifically, we emphasize that no one person can provide another individual with all the support they need. We are more than our science and therefore need mentors in other parts of our lives. We work with all participants to build individualized mentor maps, helping them identify the many members of their community who already provide support, as well as areas where they may be missing someone. We then collectively brainstorm how to fill the gaps strategically and work with participants on how to approach potential new mentors.

This approach recognizes the benefits of multiple mentors and conveys why it's best not to rely on a single mentor for all needs. It also provides opportunities to discuss what mentorship is and who can serve as a mentor. Broadening their networks can increase students' sense of belonging and their intention to stay in the field [*Estrada et al.*, 2018]. It can also help reduce racial isolation and positively affect students' persistence in STEM [*Gasiewski et al.*, 2010].

We found that the greatest gains in scientific identity and reported interest in staying in the field by PROGRESS participants were experienced by those who not only were taught the value of mentorship during a PROGRESS workshop but also were paired with a local, same-gender mentor [*Hernandez et al.*, 2020]. In some cases, though, we have found it challenging to recruit enough same-gender mentors for all participants. Anecdotally, this difficulty has arisen not because of a lack of interest by prospective mentors but, rather, because of the amount of service in which these individuals were already engaged. This result points to an often discussed but unaddressed challenge in STEM: Women, especially women of color, often do far more of the unpaid labor of mentoring than their colleagues [*Hirshfield and Joseph*, 2012].

Not everyone in the STEM community is prepared to be an effective mentor, in part because the work of mentoring in science is undervalued. It is critical that we collectively increase our community's valuation of and capacity for mentorship. To that end, the PROGRESS team also provides 1-hour mentor training to faculty, graduate students, and professionals.

Beyond the efforts of PROGRESS, we suggest that the community can more appropriately value those who develop the skills (including learning to shoulder the emotional toll) and take the time to mentor the next generation of scientists by ensuring that these activities are recognized and accounted for in workload distributions and considerations of recognition and career advancement.

Forward PROGRESS

Systematically improving mentoring will be a critical part of retaining undergraduate students in the geosciences and overcoming the field's persistent diversity challenges. The development, iteration, and testing of PROGRESS have indicated that all mentoring efforts should encourage broad representation to help students build their science identity, provide early engagement and access to resources, explain the societal relevance of the geosciences, and intentionally establish communities of support.

We will continue to grow the number of regions and institutions involved in PROGRESS and update the community as we identify additional critical and transferable attributes of the program. We welcome new partnerships with those interested in working together to further transform the way we welcome the next generation of scientists.

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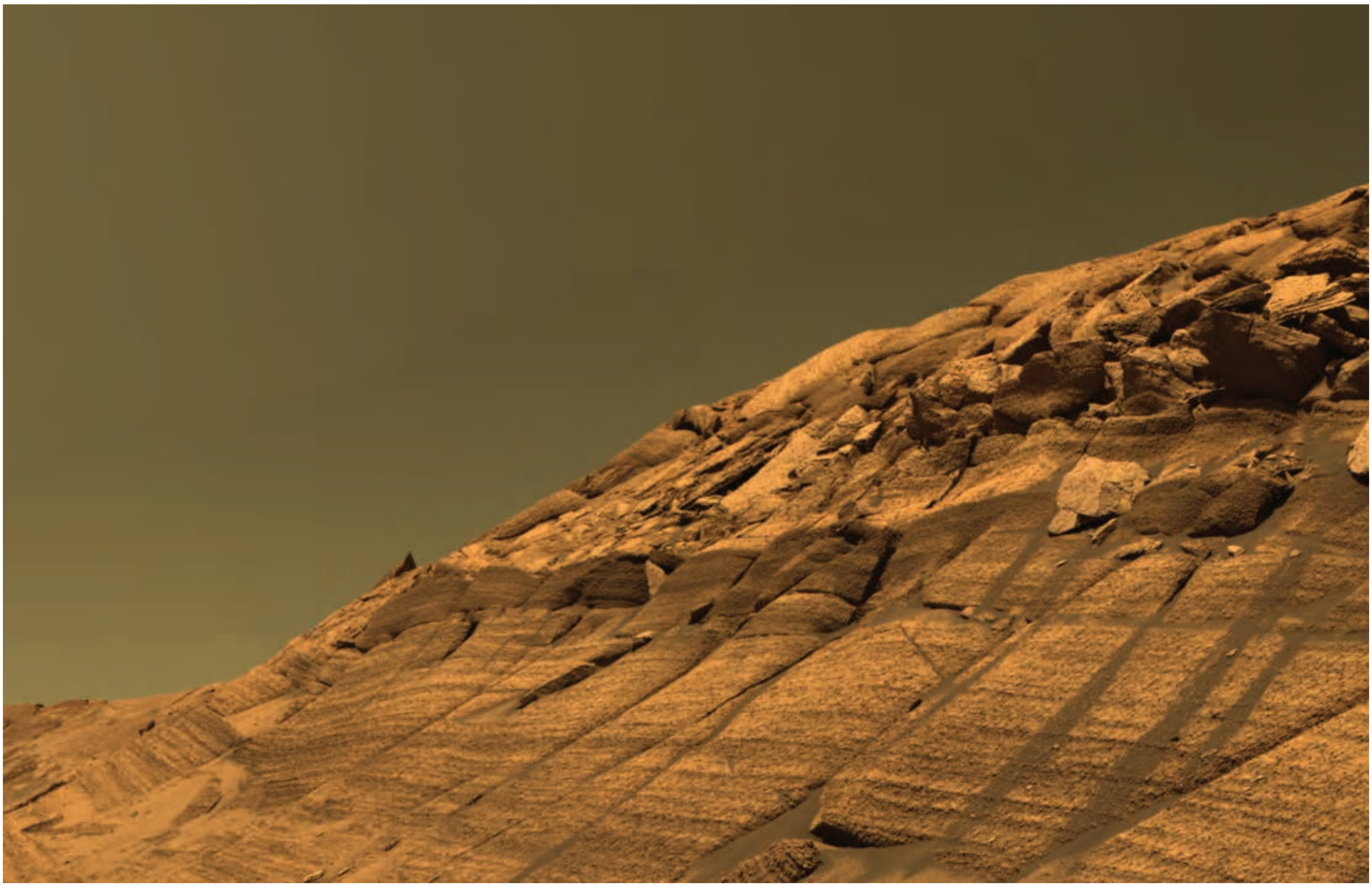
A New Origin Story for Mars's Burns Formation



NASA's Opportunity rover collected valuable data on the Burns formation, including this image of Burns Cliff. Credit: NASA/JPL/Cornell, Public Domain

NASA's Opportunity rover explored Mars's Meridiani Planum region for 14 years for a reason: The locale could hold crucial hints about the Red Planet's early geology and environment.

The region's Burns formation, a layer of sandstone embedded with spherules of hematite referred to as blueberries, is of particular interest to scientists because it shows hallmarks of liquid water and has a sulfur-rich composition that echoes features common across Mars.

The Burns formation lies atop a thin rock layer called the Grasberg formation, and in a new study, *McCollom and Hynek* propose a novel, common origin story for the two.

The idea is based on the recent finding that the Burns and Grasberg rocks are chemically similar, except that the former are enriched in magnesium and sulfate.

Previously, two main hypotheses explained the Burns formation's chemical composition. One family of models suggested that the original sands were a combination of ancient silicates and sulfate salts of iron, magnesium, and calcium that precipitated from evaporating groundwater on the margins of ancient lakes. A second group of models proposed that the sandstones began as basaltic ash and were transformed through the addition of volcanic or atmospheric sulfuric acid.

The authors of the new study put forth a third possibility, that the two formations may come from the same source material, or at least a very similar one. They propose that the Burns/Grasberg precursor was deposited onto Meridiani Planum as particles of dust or falling ash from nearby volcanic eruptions. These materials solidified, were weathered to the size of sand grains, and were blown by the wind to their current location. Once settled, the sand dunes experienced periodic flows of groundwater, which enriched the upper layers in magnesium and sulfate. Water flow also cemented the sediments to form the sandstones observed by Opportunity.

The study's authors constructed a mass balance model simulating this scenario and, using data collected by Opportunity's Alpha Particle X-ray Spectrometer, determined that the new hypothesis better matches Opportunity's observations than other previously proposed mechanisms do.

The findings could shift how scientists think about the environmental conditions on early Mars and transform interpretations of the origin of sulfate-rich deposits found elsewhere on the planet. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2022JE007374, 2023)
—Morgan Rehnberg, *Science Writer*

Short-Lived Solutions for Tall Trees in Chile's Megadrought

For more than a decade, forests across much of Chile have been experiencing a megadrought, its effects overprinted on an already warming and drying climate. High in the Andes, stands of giant *Nothofagus obliqua* trees, also known as roble or southern beech, are stretching themselves to survive—and bucking a global forest trend.

Many trees have experienced decreased growth rates, but some Chilean beeches, which can grow to heights of 40 meters (131 feet), have not. However, researchers report in a new study, not all stands stand equal chances of success in coping with the climate.

Urrutia-Jalabert et al. studied five stands of *N. obliqua* across a 500-kilometer-long section of the Chilean Andes that spans both Mediterranean and temperate climates. The researchers analyzed carbon and oxygen isotopes in the trees as well as the widths of tree rings dating from 1967 to 2017. These indicators reflect the amount and source of precipitation a tree has received, and together they can reveal how a tree has survived.

Isotopic data suggested that the most resilient *N. obliqua* stands maintained steady growth rates by pulling moisture from deeper water sources and keeping their leaves' stomata more closed, which minimizes water loss while taking in necessary carbon dioxide. Both mechanisms were important, the researchers found. One stand of beeches in a temperate region, for example, showed exceptionally efficient water use with its leaves, but the trees' growth rates still dropped, likely because of limited water availability in the soil, the authors said. The most resilient stand, farther north in a Mediterranean climate, used both mechanisms to keep growing.

Sourcing deeper water might be only a temporary fix, however. As droughts become longer, more frequent, and more severe, those reserves may run dry. In addition, trees relying on deeper water may receive fewer nutrients, stymieing their development even if they are getting enough water.

Scientists studied stands of roble beech trees (Nothofagus obliqua) like these across a variety of climates in the Chilean Andes to understand how the trees have responded to long-term drying and a recent megadrought. Credit: Rocío Urrutia-Jalabert

So although some trees have successfully adapted to drought in the short term, it's unclear how long they'll be able to continue. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2022JG007293, 2023) **—Rebecca Dzombak,** *Science Writer*

Coral Chemistry Reflects Southeast Asia's Economic Expansion

Economic expansion leaves indelible marks on coral chemistry, according to a new study. By analyzing barium levels in coral cores, scientists can access decades-old records of regional development and erosion rates.

East and Southeast Asia have experienced rapid development over the past 6 decades. Cities in the region have sprawled, forests have disappeared, and agricultural fields have spread, leading to the fastest soil erosion rates in the world. Experts predict that the rates will continue to increase.

Understanding where and how quickly soil is eroding is important for rapidly developing countries to sustain their agricultural output, but for many parts of East and Southeast Asia, long-term records are lacking.

Corals, it turns out, have been keeping track. When sediments from land make it to the sea, they carry with them elements such as barium. Those elements change the ocean's chemistry and enter the skeletons of corals and other shallow-sea animals. Because barium is largely sourced from continents, its prevalence in coral skeletons could reflect the erosion of sediments from land to sea.

Li et al. present a new multidecadal record of erosion based on barium concentrations and isotopes from coral cores. The cores came from the South China Sea near southern Taiwan and central Vietnam. Each one provided about 2 decades of data recorded at a monthly resolution.

The core from Taiwan preserved coral growth between 1980 and 2004. From 1980 to about 1995, both Taiwan's gross domestic product (GDP) and coral barium content increased, suggesting a link between development and erosion. Starting in 1996, GDP continued to grow but erosion decreased. That decoupling could reflect effective soil conservation efforts, the authors say.

The Vietnam core, which recorded growth between 1978 and 2003, also showed a correlation between economic development and erosion. From the 1990s to the 2000s, Vietnam's urban areas grew about tenfold, and the coral's record of erosion increased as well.

Corals contain an important historical record of erosion and economic expansion, but with threats of climate change, ocean acidification, and sediment input looming large, their dutiful watch may soon be imperiled. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2022JC019397, 2023) **—Rebecca Dzombak,** *Science Writer*

Tree Ring Width Predicted by Machine Learning

Each year, a tree grows a layer of dark and light wood. Credit: Monika Grabkowska, Unsplash

Tree rings are records of annual growth, and the width of each ring correlates to that year's environmental conditions. In a new study, *Lee and Dannenberg* used machine learning to demonstrate that ring width is well correlated with the types of air masses a tree experienced over that year.

Previously, scientists linked tree ring variability to discrete climatic elements like temperature, precipitation, and drought. However, weather is experienced not as individual elements but as a collective of different components. The integrated experience of weather can be characterized as an air mass: atmospheric bodies thousands of kilometers in size.

In the new study, the authors gathered tree ring records for 130 species across 904 observational sites in the Northern Hemisphere. They also pulled weather data on the air masses at each site and on each day dating to as far back as 1979 using a publicly available data set called the gridded weather typing classification. This system sorts weather into 11 types based mostly on temperature and humidity.

Then, using artificial neural networks, the researchers correlated a tree ring's width to the number of days the tree experienced each different class of air mass over the preceding 12 months. For comparison, they used the same machine learning approach using traditional temperature and precipitation data.

The air mass approach outperformed the traditional one for 66% of tree species. That percentage rose to 83% among the species with the most available records. The researchers' analysis revealed that humid-cool air masses were most correlated with significant tree growth, and dry-warm air masses were most predictive of poor growth.

The researchers used the model to glean how past climate conditions affect tree growth, but they note that the directionality could be reversed: The tree ring record extends to nearly 14,000 years, and it could be used to classify ancient air masses.

The findings could be used even to peer into the future. By characterizing current air masses and forecasting future ones, the model could gauge plant stress, mortality risk, and wildfire vulnerability for the coming year. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2022JG007064, 2023)

—Morgan Rehnberg, *Science Writer*

How Space Storms Miscue Train Signals

In July 1982, train signals in Sweden misfired and erroneously turned red. The culprit, believe it or not, was a space storm that started 150 million kilometers (93 million miles) away.

Explosive events on the Sun can disrupt Earth's magnetic field. They send magnetized solar material hurtling toward Earth. A space storm, or geomagnetic storm, occurs when this material perturbs our planet's magnetic field. This perturbation can induce electrical currents at Earth's surface that can disrupt power lines, pipelines, train tracks, and more.

Train track disruptions are particularly troublesome because space storms can interfere with detection systems that prevent collisions. Railways detect trains using electrical currents and send stop signals to them to avoid crashes. But when Earth's magnetic field is disrupted, they could send false signals to stop or go, affecting operations and potentially endangering the freight and passengers on board.

Patterson et al. developed a model to test how strong a geomagnetic storm must be to disrupt railways and how often one might occur. The model, which simulates how space storms affect electrical signals, is based on two real-life railway lines in the United Kingdom with different orientations and geography.

The researchers found that along both modeled lines, a space storm strong enough to disrupt a railway signal occurs about once every 30 years. More extreme storms—expected to occur once every 100 years—disrupt nearly all signals along both lines.

These findings could help scientists and regulators assess how vulnerable trains are to cosmic geomagnetic disruptions and spread awareness among operators. (*Space Weather*, https://doi.org/10.1029/2022SW003385, 2023) **—Sarah Stanley,** *Science Writer*

How to Build a Climate-Resilient Water Supply

Shown here is a flooded road in Kingston, Jamaica, in the aftermath of Hurricane Dean in 2007. Infrastructure investment is required to make Jamaica's water supply sector more resilient in the face of the increasing frequency and severity of extreme weather events, such as floods. Credit: Christina Xu, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

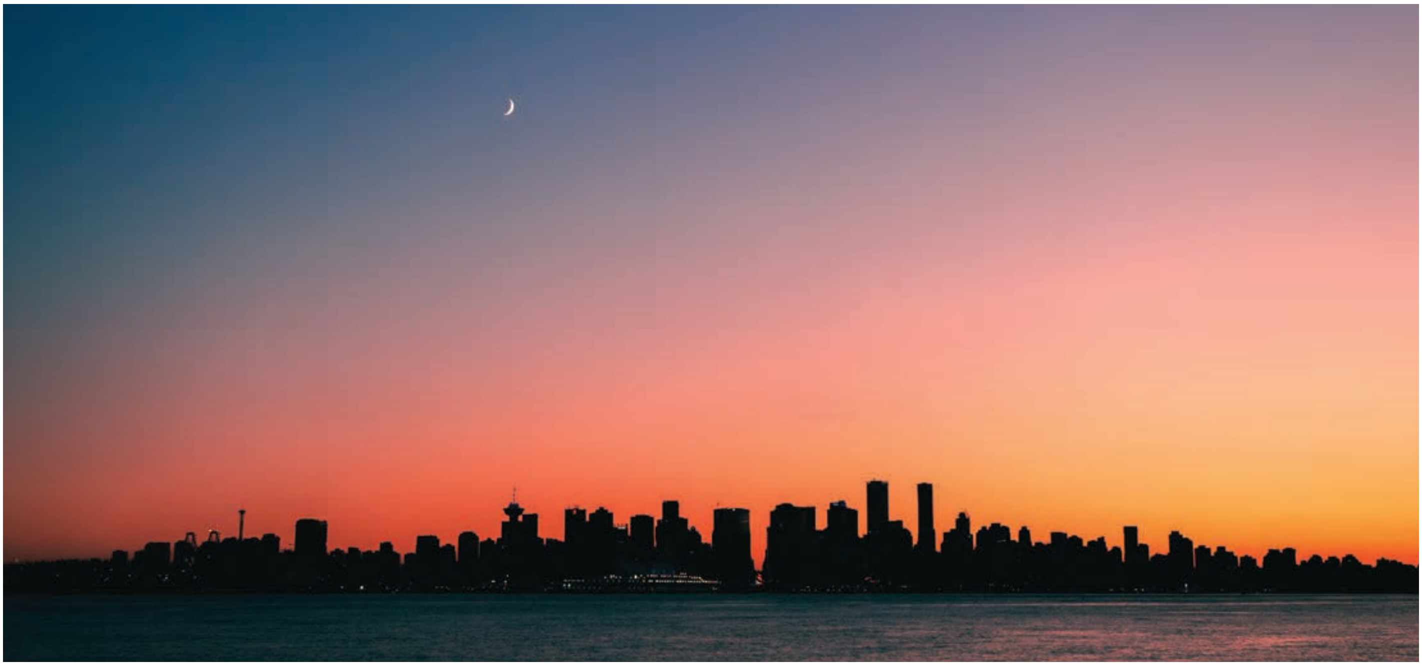
Jamaica will likely face more frequent and intense extreme weather events over the coming decades because of climate change. Such events, including flooding and drought, could strain the country's water infrastructure and disrupt access to clean water. To help these systems become more resilient in the face of climate change, *Becher et al.* developed a model to quantify how extreme weather events would affect Jamaica's water infrastructure.

The researchers found that Jamaica's utility customers currently experience an island-wide average of 5 days of climate-related water supply disruption per year, and climate change will exacerbate this situation. Even in a best-case carbon emissions scenario, disruptions could double by the end of the century. Under more pessimistic scenarios, disruptions could increase by a factor of 2.5.

The actual disruptions that customers might experience vary spatially and depend on the type of weather event. Infrastructure damage due to a cyclone, for example, would cause acute and widespread water supply disruptions. Meanwhile, disruptions from drought might be more frequent and protracted.

The authors say they hope that their study informs and promotes investment in climate-resilient water infrastructure in Jamaica. Finding and fixing leaks in aging water pipes, for instance, could improve resilience to drought conditions, and flood barriers could mitigate the impacts of cyclones. Such adaptive measures could save millions of people from going days without clean water. (*Earth's Future*, https://doi.org/10.1029/2022EF002946, 2023) **—Rachel Fritts,** *Science Writer*

Mental Illness Can Be Deadly During Heat Waves



During the 2021 extreme heat event that struck Vancouver, shown here, and most of British Columbia, Canada, residents with some mental illnesses were especially vulnerable. Credit: Luc Tribolet, Unsplash

For one devastating week in June 2021, parts of western North America reached almost 50°C (122°F). The consequences of the extreme heat event went far beyond discomfort. In British Columbia, Canada—one of the hardest-hit regions—1,649 people died over an 8-day period (almost double the norm), putting the heat wave among Canada's deadliest weather events.

But according to a new study, not everyone faced the same risk of dying. *Lee et al.* compared the prevalence of 26 chronic diseases among people who died in British Columbia during the extreme heat event with their prevalence among people who died during the same dates in previous years. They found that mental illnesses were among the conditions that left people most susceptible.

The researchers analyzed administrative health data associated with about 8,000 deaths and found that people with schizophrenia were 3 times more likely to die during the heat event than during more typical summer weather.

There also were more nuanced links to mental illness. For example, depression was associated with nearly twice the likelihood of death from heat. When the researchers considered cases in which the cause of death was listed as "pending" (a common situation caused by reporting delays), they found that people with substance use disorder had a 1.5-fold increase in the likelihood of death.

Several other studies have linked mental illness to death during extreme heat, but it's not entirely clear why this association exists. Some mental illnesses, including schizophrenia, are associated with a condition called anosognosia, which inhibits a person's insight into their own health status. The authors hypothesize that this may leave people unable to perceive the risks of overheating. Furthermore, people with mental illnesses are often stigmatized, isolated, and economically marginalized, which are all risk factors during extreme heat. Finally, antipsychotic and antidepressant medications, which are necessary to manage some mental illnesses, can affect thermoregulation, so these drugs may leave patients susceptible to overheating.

In addition to mental illnesses, the new research identifies other conditions associated with higher likelihood of death during this heat event, including chronic kidney disease, ischemic heart disease, chronic obstructive pulmonary disease, ischemic stroke, and diabetes. In a surprising result, they found that people with dementia, the cardiovascular conditions angina or hospitalized transient ischemic attack, or osteoporosis were less likely to die during the 2021 heat wave than during typical summer weather.

Previous work has shown that dementia and cardiovascular disease increase the risk of death. It's possible that caregivers paid extra attention to people with these ailments during the 2021 heat wave because of those known links, but the researchers were not able to confirm this possibility with the available data. The hope, according to the scientists, is that people with mental illness will receive such life-saving attention during future natural disasters. (*GeoHealth*, https://doi.org/10.1029/2022GH000729, 2023) **—Saima May Sidik,** *Science Writer*

Dear AGU:

In fall 2020, I visited the Beartooth Mountains in Montana with my friend and colleague Erika Rader of the University of Idaho. We were scouting out field trip stops in the Stillwater Complex, a layered mafic intrusion (which are super rare on Earth!).

—**Madison Myers,** assistant professor, Department of Earth Sciences, Montana State University

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