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Eos

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How Stone Age Humans Chose Their Stones

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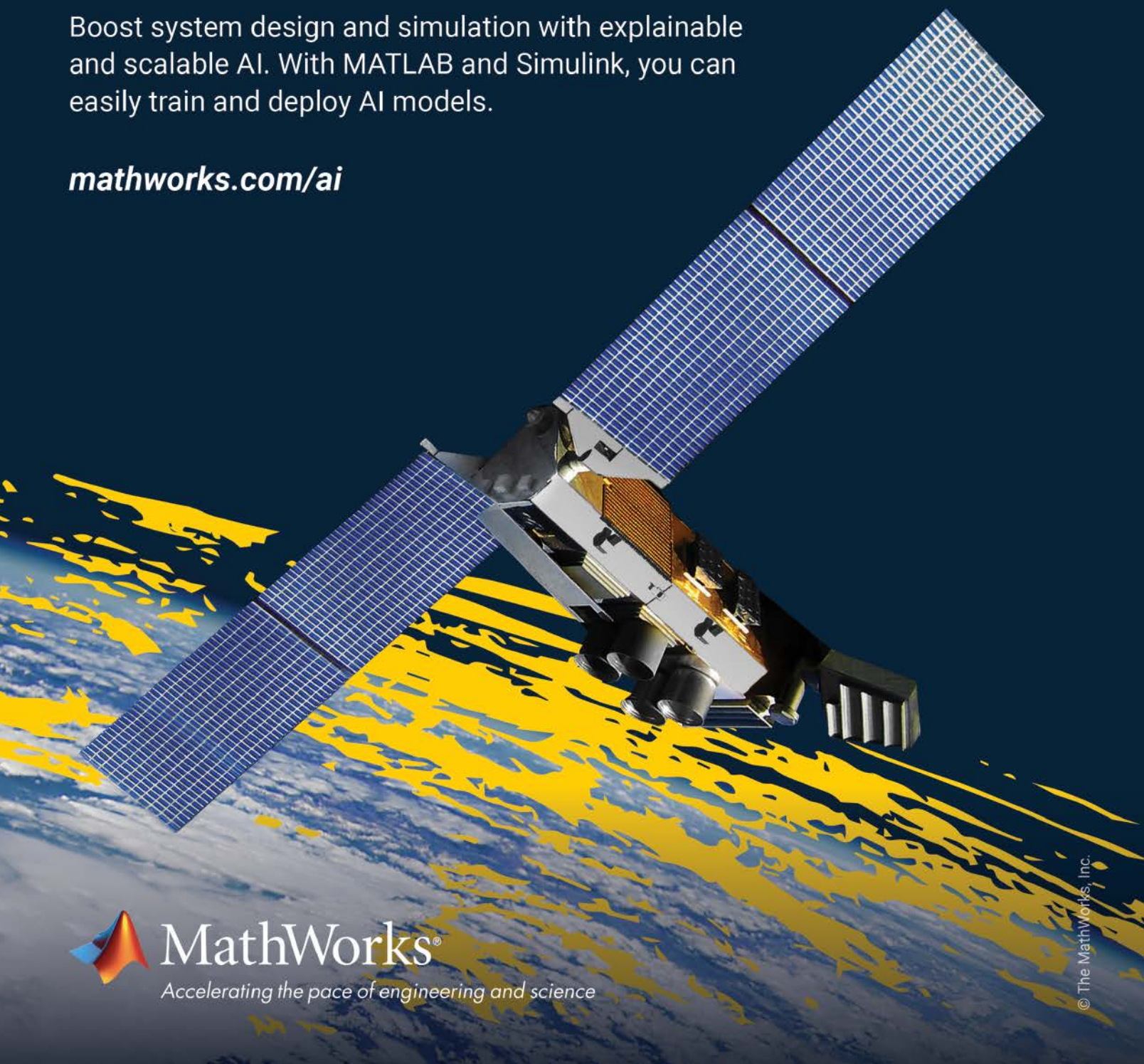

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From the Editor

How we evaluate risk depends on our background and lived experience. In this issue of *Eos*, we explore how effective science communication recognizes and responds to risk perception in different communities. When the Marshall Fire literally brought debris to their doorsteps, Colorado geoscientists responded to neighborhood concerns about air quality with empathy—as well as with monitoring equipment and scientific diligence. More than 2,000 kilometers away, volcanologists and emergency managers in Mexico are sharing specific risks posed by Popocatépetl, acknowledging residents' differing life experiences and current responsibilities. Both approaches balance humanity with scientific rigor and respect.

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After the devastating Marshall Fire, these scientists pooled their knowledge to answer new questions and help their community.

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The active stratovolcano Popocatépetl is seen from the city of Puebla in central Mexico. Credit: iStock.com/Spacewalk

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Caryl-Sue Micalizio, Eos_EIC@agu.org

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Janice Lachance, Interim Executive Director/CEO

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Ocean Pollution Makes Microbes Adapt

For several hot July days in 2016, microbiologist Sabine Matallana-Surget swam in the waters near Pensacola Beach, Fla., with plastic bags full of seawater, crude oil, and a cleaning agent called Corexit. By floating these materials on the Gulf of Mexico's surface, she simulated the marine environment as it existed during the 2010 Deepwater Horizon disaster.

In the wake of that environmental catastrophe, airplanes dumped nearly 2 million gallons of Corexit on the Gulf of Mexico to break up the slick. Its effect on the oil-eating bacteria that ultimately cleaned the ecosystem of contaminants is largely unknown.

By deploying her carefully curated bags, Matallana-Surget, an associate professor of environmental molecular microbiology at the University of Stirling in Scotland, was working to incubate microbial communities and see how they developed in the first 24 hours after exposure to crude oil, Corexit, and large doses of ultraviolet (UV) radiation.

Results of this research were published in *Frontiers in Marine Science* (bit.ly/bacteria-oil).

Current studies have shown that the Roseobacteraceae family of bacteria put the *b* in biodegradable (bit.ly/PAH-biodegradation). They have an appetite for hydrocarbon and ought to proliferate in the wake of an oil spill—at least in theory.

Sabine Matallana-Surge (right) and Philippe Lebaron position experiments near Pensacola Beach, Fla., testing the response of microbial communities to crude oil and dispersants. Credit: Wade Jeffrey

"It didn't create an incredibly toxic soup. But it wasn't harmless either."

But "just because it happens in the lab doesn't mean it will work in the field," cautioned Wade Jeffrey, director of the Center for Environmental Diagnostics and Bioremediation at the University of West Florida and a coauthor of the paper. "You could grow cultures of bacteria in the lab that would eat anything. In the natural world, that doesn't work the same because there's lots of other things that are easier to eat than these complex organic compounds," he said.

To examine what happened inside the bags, Matallana-Surget borrowed a technique from medical science that checks the health of bacteria by profiling their DNA-expressed proteins.

"We didn't have any idea how the UV and the oil and the Corexit were all going to interact. It didn't create an incredibly toxic soup. But it wasn't harmless either," Jeffrey said.

Environmental Dependencies

In the field, some bacteria showed a remarkable ability to produce oil-digesting enzymes in all conditions, whether under intense UV radiation, shocked with Corexit, or both.

In particular, species in the orders Alteromonadales and Oceanospirillales flourished by virtue of several different adaptations. Their efficient DNA repair mechanisms, tolerance of oxidative stress, and omnivorous capacity to metabolize foods from different sources gave them an advantage over bacteria, like *Roseobacter,* that fared better in the lab than in the gulf.

Rhodovulum, another common oil degrader, succumbed to UV radiation. Others perished because of Corexit and did so in a fashion that surprised Matallana-Surget.

"I study a lot of different stressors, and I've never seen that many stressors when it comes to the DNA damage induced by Corexit," she said.

Zhanfei Liu, a professor of marine science at the University of Texas at Austin, applauded Matallana-Surget's use of protein sequencing to reveal how some bacteria survive and thrive. "This work is a major contribution to the field, and in addition to oil spill science, it also offers insights into how microorganisms work in marine environments," he said.

Matallana-Surget said that policymakers should start asking questions like, Will sunlight affect and modify the chemicals already in the sea? Is the spill in a place where bacteria that are naturally present could degrade the oil? Should we add tons of Corexit or just enough to biodegrade the oil? She hopes her findings lead to more informed disaster mitigation strategies.

By **Martin J. Kernan,** Science Writer

A Long-Lost Tropical Island Lies off Brazil's Coast

In 2018, Brazilian and British scientists were exploring the seafloor around a volcanic plateau known as the Rio Grande Rise when they spotted rocks that looked like they belonged on dry land.

As the researchers watched video relayed from their remotely operated submersible 650 meters (2,100 feet) below the surface, unusual red clay layers caught their attention. "You just don't find red clay on the seabed," said Bramley Murton, a marine geologist at the National Oceanography Centre in Southampton, U.K., who was on the expedition. "The deposits looked like tropical soils."

In a recent study, the team showed that the clay's distinctive mineral makeup could have formed only by open-air weathering in tropical heat and humidity (bit.ly/Rio-Grande-Rise-clay). It's the latest in a string of discoveries hinting that this patch of the Atlantic Ocean, 1,200 kilometers (750 miles) from Brazil's coast, was once an island.

Volcanic Origins

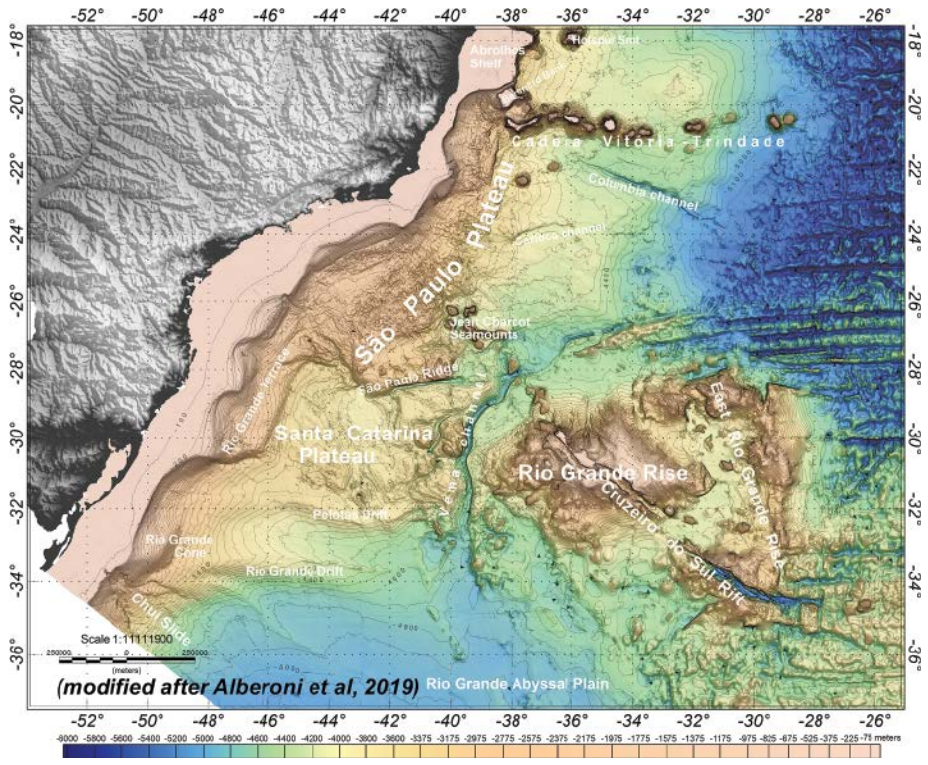
"Imagine a lush tropical island slipping beneath the waves and lying frozen in time. That's what we've uncovered," said Murton, a coauthor of the study. He and colleagues think the island would have been similar in size to Iceland (about a fifth of the Rio Grande Rise's total area).

The origins of the Rio Grande Rise go back 80 million years. An enormous mantle plume sat beneath the South Atlantic's mid-ocean ridge, causing a burst of intense volcanism; the resulting rise "started life as a Cretaceous version of Iceland" closer to the mid-ocean ridge than what is now South America, Murton said. Gradually, as volcanic activity subsided, the volcanic plateau drifted west across the Atlantic and sank beneath the waves.

But starting around 40 million years ago, the mantle plume had one last gasp of volcanism, this time isolated to the western portion of the rise. This area is where the researchers found the red clays, sandwiched between lavas known to be about 45 million years old.

"This is an outstanding result," said Luigi Jovane, a marine geologist at the University of São Paulo and a coauthor of the study. "The red clays are conclusive proof that this was once an island." Jovane has been leading investigations in the Rio Grande Rise for more than a decade.

Researchers captured images and samples of the seabed around the Rio Grande Rise with a remotely operated vehicle. Red clay, hinting at the area's earlier existence as an island, pokes out from beneath the black basaltic lava. Credit: Luigi Jovane



This bathymetric map shows seafloor features along the Brazilian meridional continental margin, including the Rio Grande Rise. Credit: Ana Alberoni, modified from Alberoni et al., 2019, https://doi.org/10.1007/s00367-019-00606-x

Underwater Exploration

The research is the culmination of two scientific expeditions to the rise in 2018. The first, aboard the Brazilian research vessel *Alpha Crucis*, mapped the rise's underwater terrain using sonar. That project was initially aimed at characterizing mineral-rich ferromanganese crusts known to occur on the seafloor of the rise.

Mapping revealed a 30-kilometer-long (20-mile-long), steep-sided canyon bisecting the rise—the Cruzeiro do Sul Rift—as well as ancient beach terraces, wave-cut platforms, and drowned waterfalls.

Eight months later, the team returned aboard the RRS *Discovery*, from the United Kingdom's National Oceanography Centre. That vessel is equipped with a remotely operated vehicle (ROV), which allowed the researchers to capture footage of rocks exposed in the steep-sided canyon walls. The ROV also has a robotic arm for collecting samples.

Most investigations of seabed geology rely on sonar mapping and dredging for rock samples, said Tony Watts, a marine geologist at the University of Oxford who was not involved in the study. But "by using an ROV, [the researchers] could be more confident

about the location and context of the red beds."

Armed with a sample of the red clay, the researchers measured its mineral composition back in the lab. They found that it mostly contained a type of clay mineral called kaolinite, which dominates tropical soils because it is resistant to extreme chemical weathering.

"These red clays are exactly the same, chemically and mineralogically, as the red earth, or *terra roxa*, we find all over Brazil," Jovane said. "We are confident that they represent the in situ, weathered upper surfaces of the lavas."

"This is a robust dataset," said Watts, who agreed with the team's interpretation that this area was once above sea level. He added that the research has important implications for understanding the magmatic and subsidence history of the rise.

Evidence collected in the 1980s, including drill cores containing shallow-water microfossils, had indicated that the western part of the rise was uplifted during the Eocene, Murton said. But "no one has found convincing evidence for subaerial volcanism and exposure of the western rise until now."

Coveted Minerals

The Rio Grande Rise is more than just scientifically fascinating. It also has potential economic value owing to its ferromanganese crusts. In December 2018, the Brazilian government applied to the United Nations to extend its maritime borders to include the Rio Grande Rise.

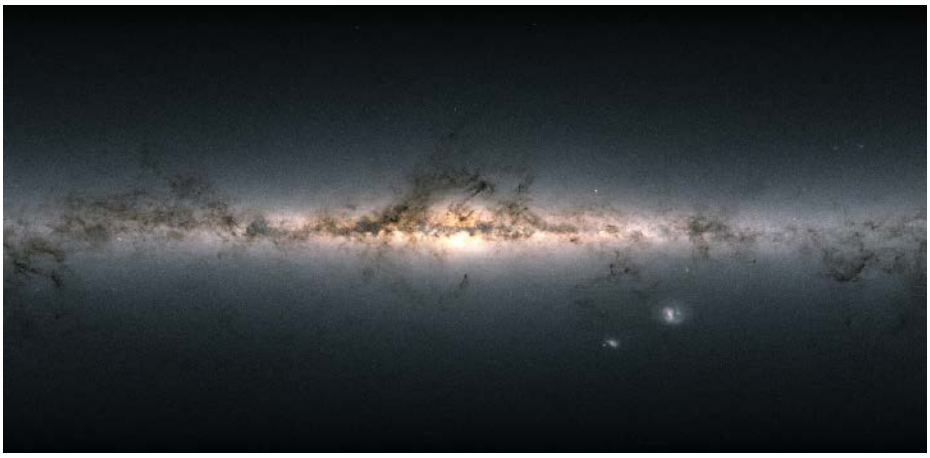
The rise is located in international waters and is well beyond Brazil's 370-kilometer-wide (200-nautical-mile wide) exclusive economic zone—the area over which coastal nations have sovereignty. To qualify for an extension, Brazil needs to prove that the rise has the same geological characteristics as the nation.

The rise's newfound status might help bolster that ongoing claim. "The Rio Grande Rise and the continent have the same soil and climate," explained Jovane. "In that sense, there is a direct relationship between the two."

Jovane said Brazil needs to prove not only that it has a correct claim to the Rio Grande Rise but also that it can mine the area sustainably. Currently, Brazil has regulations for mining only on land, and there is still no legislation for seabed mining in international waters.

By **Erin Martin-Jones,** Science Writer

Passing Stars Shorten Earth's Time Horizon



Year after year, the solar system's planets move around the Sun in a seemingly steady and unchanging orbital dance. But the Sun, planets, major moons, and dwarf planets constantly exchange gravitational energy and can subtly shift each other's orbits on thousand- or million-year timescales.

How well scientists understand these shifts determines how far back, or forward, in time they can reliably trace planetary orbits—a point known as the time horizon.

"There's a certain time frame beyond which you can't rewind the clock anymore," explained Sean Raymond, an astronomer at the Laboratoire d'Astrophysique de Bordeaux and Université de Bordeaux in France.

The most precise calculations of Earth's time horizon require the most precise measurements of solar system bodies. This includes everything from the Sun's slightly nonspherical shape to the sizes and positions of planets, moons, dwarf planets, and major asteroids.

Recently, astronomers demonstrated that a new factor should be considered when calculating Earth's time horizon: other stars whizzing past the solar system. Gravitational wakes induced by these stellar close encounters could shorten Earth's time horizon by up to 10%, or 7 million years, according to a study published in *Astrophysical Journal Letters* (bit.ly/passing-stars).

Precise knowledge of Earth's orbital past is key for understanding the solar system's history and the planet's paleoclimate, which was affected by subtle changes in its orbit.

From Order, Chaos

When trying to peer back in time, precision matters. Even the tiniest uncertainty in an object's mass or position today will grow exponentially as an orbit is traced back millions of years until, eventually, past orbits become too chaotic to track, explained the study's lead author, Nathan Kaib, a planetary scientist at the Planetary Science Institute in Tucson, Ariz., and the University of Oklahoma in Norman.

> **"There's a certain time frame beyond which you can't rewind the clock anymore."**

The same principle applies to weather forecasts: Small uncertainties in weather prediction models mean that a forecast probably isn't reliable beyond more than a few days out. That's its time horizon.

Astronomers know the positions of solar system objects sometimes to within a meter, but "an error of a meter in Jupiter's position propagates, and so we can't rewind the clock as far back as we want," said Raymond, coauthor on the recent study.

Astronomers widely view Earth's time horizon as 60–70 million years (bit.ly/Earth-time-horizon). Beyond that, Earth's orbit is

too uncertain for astronomers to trace or for paleoclimatologists to ascribe as the cause of major climate shifts. (This is not linked to the current rapid climate change caused by human-emitted greenhouse gases.)

However, the most precise time horizon calculations assume that the solar system exists in isolation, unaffected by the goings-on of the Milky Way, Kaib said. But astronomers know that the Sun has been visited by other stars in the past and estimate that an average of 20 stars come within about 3 light-years of the Sun every million years (bit.ly/stellar-encounters). How much gravitational influence they may have on the solar system and thus how they affect Earth's time horizon have been unclear.

Winding Back the Clock

Using computer simulations, the team traced Earth's orbit back 150 million years, accounting for gravitational influences of the planets, Pluto, and several major asteroids. They found that Earth's orbit became too uncertain to track after about 67 million years—in line with past time horizon calculations.

Then they placed their simulated solar system in the solar neighborhood and let stars travel past as they do in reality. The team found that if a passing star was large enough, moved slowly enough, or came within several light-years of the Sun, its gravity would jostle the orbits of the outer planets. Those orbital jitters affected Earth's orbit in turn and shortened its time horizon by 5–7 million years, or 7%–10%.

"The study is interesting and suggests that passing stars may need to be added to the list of small effects on the solar system's orbital evolution," said Richard Zeebe, a physicist at the University of Hawai'i at Mānoa in Honolulu. Orbital evolution models already include minor influences from asteroids, solar quadrupole moment, tidal dissipation, and solar mass loss, added Zeebe, who was not involved with this study.

Time to Adjust the Horizon? Not Yet

The authors demonstrated that a chance encounter between the Sun and another star can, theoretically, alter Earth's orbit. But has it actually happened?

The most recent data from the European Space Agency's Gaia mission, which is mapping the positions and motions of millions of stars in the galaxy, showed that the Sun-like star HD 7977 passed by the solar system around 2.8 million years ago.

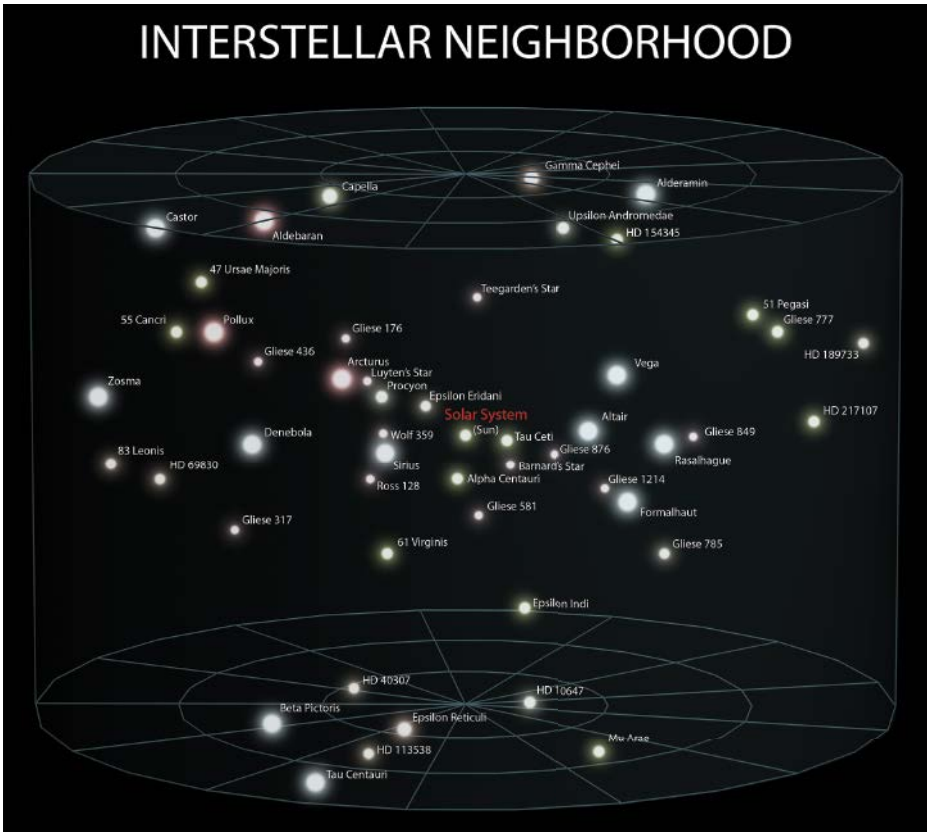
It's uncertain just how close it came, but there is a small (5%) chance that it passed within 3,900 astronomical units (a distance less than one light year), or about 100 times the distance between the Sun and Pluto. The team's simulations showed that if HD 7977 passed that close, the star's gravity would have rippled through the solar system, stretching Earth's orbital eccentricity a bit and shortening its time horizon to only 50 million years.

That adjusted time horizon, broadly a limit on how far back scientists can estimate the influence of Earth's orbit on its climate, put it within range of a paleoclimate shift called the Paleocene-Eocene Thermal Maximum (PETM) (bit.ly/paleoclimate-shift). Geologic records from about 55 million years ago show an increase of more than 5°C in global average temperature that might have been caused by a change in Earth's orbital eccentricity (bit.ly/orbital-eccentricity).

Zeebe warned that the effects of a passing star on Earth's orbit would be subtle. "The notion that passing stars are an important driver of paleoclimate should be taken with caution." He added that "the chances that stellar encounters [like] HD 7977 are relevant to our computations or understanding of the PETM are very slim," agreeing with the study's conclusions.

The geologic data on the event describe what happened very clearly, Zeebe said. "Including stellar encounters in astronomical models could perhaps make a small difference in the computations…but not in the data," he said.

Though their simulations of Earth's orbit after an encounter with HD 7977 are consistent with the geologic record for the PETM, Kaib and Raymond said that HD 7977 did not trigger the warm period, nor do they claim that their calculated time horizon should be adopted as is. They emphasized that their model lacks many of the subtle, but important, details, such as tides and a nonspherical Sun or Moon, that go into the most sophisticated time horizon calculations.



Shown here are prominent bright stars within about 50 light-years of the Sun. This map does not include small red and brown dwarf stars, which are far more numerous. Credit: Andrew Z. Colvin, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

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

Poorer Countries Face Heavier Consequences of Climate Change

Forest biomes are on the move because of climate change, and nations from Albania to Zimbabwe will experience shifts in economic production and ecosystem-provided benefits as vegetation cover relocates—or disappears entirely. Countries could lose 1.3% of their gross domestic product (GDP), on average, according to new research. And poorer nations will face proportionally larger losses.

An ongoing poleward shift in vegetation, likely to persist into the future, has implications for natural resources such as timber, said Bernie Bastien-Olvera, a climate scientist at the Scripps Institution of Oceanography at the University of California, San Diego. "As forests migrate toward higher latitudes, many countries are losing forest cover."

As climate change causes forest biomes to move, timber resources will also shift. Credit: Mark Horrell/Flickr, CC BY-NC-SA 2.0 (bit.ly/ccbysa2-0)

"There are things that we value from nature that we do not necessarily pay to use."

Tangible and Intangible Resources

Such changes trigger not only economic effects—reduced forest cover means less timber available to sell—but also societal effects. That's because in addition to producing so-called natural capital such as wood that can be sold, forests also provide intangible resources such as clean air and water and recreational opportunities. These natural nonmarket benefits can't be quantified like salable merchandise, but they're valuable nonetheless, Bastien-Olvera said. "There are things that we value from nature that we do not necessarily pay to use."

Bastien-Olvera and his colleagues recently estimated country-level changes in both natural capital and natural nonmarket benefits for a variety of climate change scenarios. The team focused on 134 countries and considered three different warming scenarios: Representative Concentration Pathways (RCPs) 2.6, 6.0, and 8.5. Those scenarios correspond to roughly 1.0°C, 2.2°C, and 3.7°C of warming, respectively, by the end of the 21st century.

The researchers considered those different warming scenarios within the context of global vegetation models. Such models reveal how climate change will shift forest biomes, Bastien-Olvera said. "Tropical forests will replace temperate forests, temperate forests will replace boreal forests, and boreal forests will grow where there is right now only permafrost."

The Economics of Timber

To get a handle on how each country's natural capital might fluctuate in the future because of climate change, Bastien-Olvera and his colleagues mined World Bank–produced valuations of each nation's timber resources (bit.ly/changing-wealth). They then apportioned those values over every country's present-day forest cover. Finally, they estimated the economic changes each country would experience in the future as forest biomes shifted into—or out of—its borders.

With even just 1°C of warming, the team found that most nations would experience losses in their timber-based capital. Some countries, mostly in Africa, would experience losses of up to 10% by 2100. And though a handful of nations, such as Oman and Yemen, would actually benefit from the climate change, losses would predominate overall, Bastien-Olvera said. "The gains are very, very small compared with the large losses."

Shouldering More of the Burden

The researchers next examined those changes in natural capital in the context of each country's GDP. For the case of the RCP 6.0 warming scenario, they found that nations, on average, would lose about 1.3% of their GDP. That might not sound like much, said Max Kotz, a climate impact scientist at the Potsdam Institute for Climate Impact Research who was not involved in the study. "But if it's

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a persistent and permanent reduction, that's something that most economists would consider to be fairly important."

Bastien-Olvera and his collaborators furthermore showed that poorer countries were harder hit: The poorest 50% of countries shouldered 90% of GDP losses. That statistic unfortunately isn't surprising, Kotz said. "It's clear from what we know from patterns of economic development that these regions are still more dependent on their natural resources." (Natural capital constitutes less than 0.1% of GDP in relatively wealthy nations such as the United States but more than 5.1% of GDP of poorer countries such as Papua New Guinea, for example.)

"The gains are very, very small compared with the large losses."

Losses in What Can't Be Sold

The researchers next examined how each country's natural nonmarket benefits would also shift in response to climate change. To do so, they mined country-level estimates of the nonmarket value of resources such as safe water sources, recreation, and the cultural value ascribed to protected areas. They then apportioned those estimates over each nation's present-day distribution of ecosystems based on the Valuation of Ecosystem Goods and Services database.

They found that more than 90% of countries would experience losses in their natural nonmarket benefits in the RCP 6.0 scenario. And those predicted shifts were substantial: Natural nonmarket benefits would fall by about 9% on average by 2100.

The results of the study were published in *Nature* (bit.ly/unequal-climate-impacts).

Of course, climate change will affect economic spheres beyond timber resources and natural nonmarket benefits of forests, Kotz noted. Aspects such as biodiversity, labor productivity, and agricultural production should all be considered in future research, he said. "It's a really important part of the picture that [the study is] filling in," he said. "But it's really not the whole picture."

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

Stone Age Humans Chose Their Rocks with Care

Were Stone Age humans the first geologists?

Humans living in what is now South Africa 70,000 years ago possessed a surprisingly sophisticated understanding of the rock varieties that made up their world, a new study published in the *Proceedings of the National Academy of Sciences of the United States of America* shows (bit.ly/Stone-Age-tools).

Not only did hunter-gatherers of the time know how to finely craft stone tools, but they also understood exactly which rocks would yield the best combinations of ease of shaping and wear resistance for the task at hand, said Patrick Schmidt, an archaeologist at the University of Tübingen in Germany and lead author of the study.

"If you want to make something out of something, you choose the right material for it," Schmidt said. "Those processes were already in place in the Middle Stone Age in South Africa."

Schmidt and his colleagues looked at various physical properties to quantitatively compare different types of rocks used by early humans.

The approach may open new avenues of inquiry for scientists hoping to assess the capabilities of our Stone Age ancestors, said Alex Mackay, an archaeologist at the University of Wollongong in Australia who wasn't affiliated with the research. "You can unpack a whole lot more complexity and decision-making," he said. "Even from something as simple as rock choice, you're seeing dimensions in human thought that we just weren't getting at before."

Stone Age Geology

You may look at a rock and see a hunk of stone. Ancient people looked at a rock and

For thousands of years, humans made stone tools such as this silicrete point found at Blombos Cave in South Africa. Credit: Vincent Mourre/Inrap/Wikimedia, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

saw a world of possibility. Rocks could be knapped, or shaped, into knife blades, spearpoints, ax-heads, and more, allowing hunter-gatherers to take on new prey and use animal remains for clothing and other items.

Rocks give archaeologists one of our only glimpses into culture in the Stone Age, a time when "modern humans start becoming really interesting," Mackay said.

One long-standing question among archaeologists is what drove people to use different kinds of rocks for their tools. Were they simply using whatever stones were available? Or were they making more specific choices about what to use?

"Even from something as simple as rock choice, you're seeing dimensions in human thought that we just weren't getting at before."

To begin to answer these unknowns, Schmidt and his colleagues created a mathematical formula to describe rock properties, including strength, fracture toughness, and fracture variability, to show how much force is needed to flake different kinds of rocks.

They applied this flaking force calculation to four different rock types found at the Diepkloof rock shelter in South Africa, which was inhabited by Stone Age humans for tens of thousands of years beginning about 130,000 years ago. Some samples were collected from the site itself, whereas others were taken from locations tens of kilometers away. The researchers compared their data on rock properties to existing stone tools from Diepkloof to learn more about how ancient humans selected rocks for toolmaking.

Inhabitants of the shelter fashioned various kinds of rocks, including quartz, quartzite, hornfels, and silcrete. After they tested samples of each of these rocks, clear differences emerged, Schmidt said. The force required to fracture some rocks was more than 3 times that required to fracture others.

"So there are really big differences. Some of those rocks, you have to hit them really hard to make a flake. Some of those rocks, you just have to tap them lightly," he said.

Fracture strength wasn't the only factor important to ancient humans. How predictably a rock flakes and how strong the resulting tool would be also mattered. Looking at their data, Schmidt said they saw distinct patterns emerge at different points in time.

Members of the Still Bay technocomplex, who were making stone tools at the site around 71,000 years ago, seemed to prefer quartzite for their tools (bit.ly/Still-Bay). The metamorphic rock is relatively hard and fractures predictably, meaning it's possible to make durable tools from it. Still Bay points tend to be long, double-edged points likely used as spear tips and sometimes for cutting. Crucially, Schmidt said, the quartzite used to make these tips fractures easily in small volumes—like when you are knapping the edge of a flake to make a tip—but is very strong when force is applied lengthwise to a larger volume, such as when you stab something with a spear.

Later humans inhabiting the site around 65,000 years ago preferred silcrete. The rock fractures more easily, which Schmidt said makes sense given the types of tools those people were making. Members of the Howiesons Poort technocomplex made many small blades for arrowheads and spearpoints that may have been meant to break off inside prey, making the animals easier to hunt down (bit.ly/Howiesons-Poort).

"So you don't care about the resistance to fracture, because the thing is supposed to break off anyway," Schmidt said. "What you rather want is something that is really making it easy for you to make those segments."

Showing that changes in the kinds of tools line up with the qualities of the rocks they were made from adds quantitative heft to hypotheses that humans were making nuanced decisions involving stone properties more than 60,000 years ago, Schmidt argued.

"They were testing materials and trying to understand the trade-offs that come from different materials," he said.

Artifacts from Stone Age humans have been found in the Diepkloof rock shelter in South Africa. Credit: Vincent Mourre/Inrap/Wikimedia, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

"It's only when you hold a stone tool that you understand the dynamic of [its] use."

Refining Calculations

It may be too soon to make those kinds of statements about early human tool use, however, said Marina de Araújo Igreja, an archaeologist who specializes in use-wear analysis of ancient stone tools and was not involved in the study.

She said the researchers' analysis adds promising data, but knapping the rocks they sampled and testing them as tools would help to paint a fuller picture of how ancient humans used these rocks. Studies that re-create stone tools and use them for activities like cutting can help reveal how particular stones performed. That kind of practical testing is an important component of understanding ancient human toolmakers, de Araújo Igreja said.

"It's only when you hold a stone tool that you understand the dynamic of [its] use," she said.

In addition, there can be broad variations in rock properties even within rock types such as quartzite and silcrete, she said. Mackay agreed, saying future studies should take into account differences among rocks of the same category taken from different places. He added that Schmidt and colleagues' formula may help with this. Archaeologists have often assumed that rocks of one type are all the same. With a new way to quantify the properties of stone tools, they can now begin to look more critically within those categories to tease out new insights.

"I see this as a really important step forward…in the capabilities it gives us to access human decisionmaking in the past," Mackay said.

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

No Canadian Volcanoes Meet Monitoring Standards

In a new analysis of Canadian volcanoes, Mount Garibaldi in British Columbia had the highest threat level. Credit: Wikimedia Commons/Tim Gage, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

In 2005, U.S. Geological Survey (USGS) scientists analyzed 169 potentially active volcanoes in the United States to determine what risks they posed to people. They found that more than 50 U.S. volcanoes weren't sufficiently monitored, which ultimately led to vast expansions in monitoring at many of the highest-threat sites, such as Mount Hood, Mount Rainier, and Crater Lake.

Now, a similar analysis has been done in Canada. The research, published in the *Canadian Journal of Earth Sciences,* finds that even the most threatening Canadian volcanoes aren't monitored at levels recommended by internationally recognized strategies, and scientists lack important knowledge about each of the 28 volcanoes studied (bit.ly/volcano-threat-CA).

Scientists hope their results will help decisionmakers prioritize additional monitoring of Canada's most threatening volcanoes, said Melanie Kelman, a volcanologist at the Geological Survey of Canada and lead author of the new research.

Ranking Volcanic Risk

The researchers followed methods first used in the 2005 USGS analysis of volcanic risk in the United States as part of the National Volcano Early Warning System (NVEWS). For the Canadian volcanoes, Kelman and her coauthor produced an overall threat score based on the likelihood of events like lava flows, landslides, and explosions, as well as the likelihood that such events would affect people and property.

The NVEWS methodology is very familiar to volcanologists, and using it allows the Canadian volcanoes to be compared with other volcanoes worldwide, said Alison Graettinger, a volcanologist at the University of Missouri–Kansas City who was not involved in the new study.

All of the highest threat volcanoes are in British Columbia. Threats from two, Mounts Garibaldi and Meager, ranked "very high." Those of three others (Mounts Cayley, Price, and Edziza) are "high." The remaining 23 volcanoes ranged in threat level from "moderate" to "very low."

> **"It's a work in progress, no matter what country you're in, to get your monitoring up to snuff."**

The researchers then gave each volcano a "knowledge uncertainty score" based on the amount of information scientists have collected about it. Many Canadian volcanoes, including most in the very high and high threat categories, have not been studied in detail, the authors write: Mount Garibaldi, for example, is part of the well-known Cascade Volcanic Arc but one of the least studied Canadian volcanoes.

Because geologic studies typically reveal more complexity, more scientific knowledge would likely increase rather than decrease threat scores, the authors write.

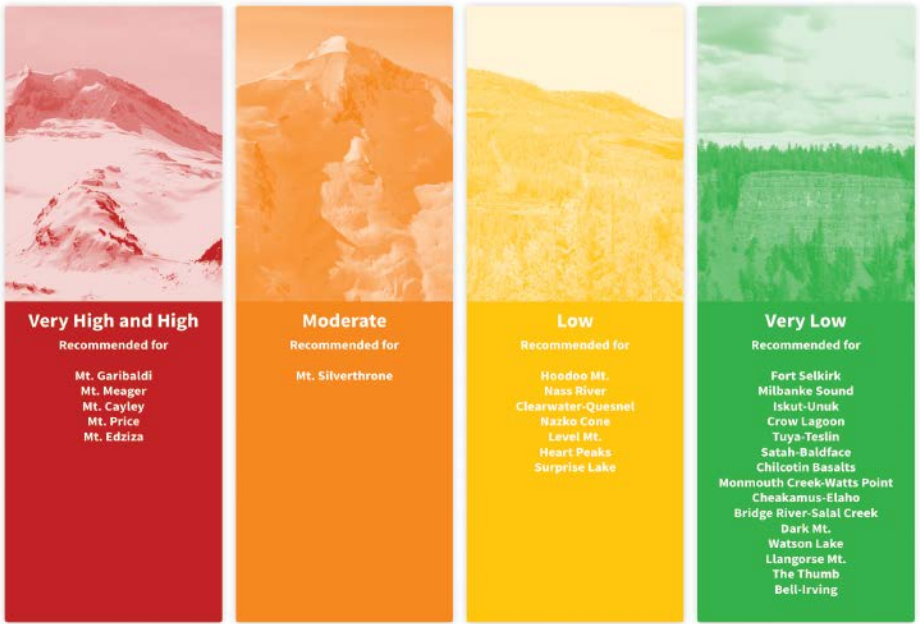
Volcanoes in the study fell far short of the recommended monitoring: Not one of the volcanoes analyzed met USGS recommendations.

In fact, no volcano except Mount Meager is monitored except for a regional network of seismographs with varied proximity to the volcanoes. Mount Meager, one of the two very high-threat volcanoes, is the most monitored, but even it meets only monitoring guidelines recommended for very low-threat volcanoes. Its monitoring activities are infrequent and conducted by different organizations, which limits data sharing.

"The ability to detect and respond to anomalous activity [at Mount Meager] is extremely limited," the authors write.

Meeting Monitoring Goals

The results aren't surprising in the context of volcanoes worldwide, Graettinger said. For example, U.S. volcano monitoring still fre-



The 28 volcanoes in Canada that were assessed in the analysis are listed from highest to lowest threat. Credit: Grace van Deelen/Melanie Kelman and Alexander Wilson

quently falls short of recommended standards from the USGS.

"It's a work in progress, no matter what country you're in, to get your monitoring up to snuff," she said.

In the U.S. Cascades region, home to some of the country's most active volcanoes, volcanologists try to match monitoring activity to threat levels, said Jon Major, a hydrologist at the USGS Cascades Volcano Observatory who was not involved in the new research. For example, activity at Mount St. Helens in Washington poses a high risk to regional aviation, so the USGS prioritizes monitoring there. "Our goal is to notify the FAA [Federal Aviation Administration] and the National Weather Service within 5 minutes of an explosive eruption," he said.

But monitoring that meets USGS recommendations requires permanent instrumentation, which is expensive and difficult to install at many sites. That's especially true in Canada, where some volcanoes are covered by glaciers or require a helicopter to access. "The remoteness is a key factor," Kelman said. "It's rugged, mountainous terrain that may be only accessible by helicopter or long-distance trekking."

Kelman said she hopes the new analysis will spur future research and monitoring, especially at the five very high and high-threat volcanoes.

Perception of Risk

Part of the challenge is risk perception: Many Canadians aren't even aware that they live near volcanoes, Kelman said. There is no living memory of an eruption in Canada, unlike in the United States, which has frequently active volcanoes in Alaska and Hawai'i and where many people, some of whom are involved in policymaking, still recall the eruption of Mount St. Helens in 1980.

"It's tough to convince people that this is necessary," Kelman said.

It's hard to convince decisionmakers to add volcanoes to their list of priorities, too, Graettinger added. "That's just a challenge across the globe. We're dealing with more people on the planet living closer to risks, not just from volcanoes," she said. "How do we get volcanoes to not be forgotten?"

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

Increasing Racial and Ethnic Diversity in Physical Geography

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Understanding the systemic complexity and broad scope of societally important geoscience challenges, such as climate change and environmental degradation, requires that teams of researchers collaborate to address large-scale questions. The discipline of geography—encompassing not just the geosciences but also remote sensing, geospatial techniques, and the social sciences—has exemplified this collaborative approach for decades.

Part of geography's success depends on the involvement of researchers with a range of scientific expertise, but it also depends on progress toward including scholars representing a diverse cross section of personal backgrounds, races, and ethnicities, an issue that has increasingly concerned geographers [e.g., *Solís and Miyares*, 2014; *American Association of Geographers (AAG) Council*, 2021].

However, the discipline's broad scope means that priorities and trends within geography as a whole do not necessarily reflect those seen across all its various subfields. And progress toward increasing diversity in the overall discipline may actually disguise a lack of such progress in certain areas. Indeed, the demographics of subfields associated with physical geography—principally, geomorphology, biogeography, and climatology—continue to be far more homogeneous than those of the general U.S. population. In other words, physical geography in the United States has a diversity problem.

The mere absence of intentional discrimination is not enough to ensure diversity.

The persistent lack of diversity in the geosciences overall has been documented and has received substantial attention recently [*Bernard and Cooperdock*, 2018; *Dutt*, 2020], although less attention has been directed toward physical geography. The scarcity of Black, Indigenous, and People of Color (BIPOC) faculty in physical geography reflects the fact that few students pursue the field as undergraduates or graduates. (We recognize that a more complete consideration of diversity would include specific attention to gender, disability, and LGBTQIA+ identities, but our discussion here primarily focuses on the BIPOC demographics.)

In our several decades of collective experience as participants and leaders in the geomorphology, biogeography, and climatology communities, we have observed that BIPOC geographers are concentrated in human, not physical, geography. This disparity presumably shows that BIPOC students are often drawn to, and remain in, human geography because of social justice elements prevalent in that field, as well as their greater exposure to it compared with STEM (science, technology, engineering, and mathematics) disciplines.

Although we hope that deliberate racial exclusion in academia has been eliminated, the mere absence of intentional discrimination is not enough to ensure diversity. Transformational change will require conscious effort, and we believe that without intentional intervention at multiple scales, physical geography will fail to effect demographic change.

Diversity Is Valued, but Barriers Remain

Increasing diversity within physical geography should be a moral imperative driven by fairness and social responsibility. But if addi-

tional incentive is needed, greater diversity can also fundamentally improve the quality and impact of the science produced and the long-term health of the discipline. Further, widening the talent pool of physical geographers is critical for addressing the complexities of environmental systems and their relations to human society.

The current lack of diversity in physical geography reflects both a lack of awareness of the field among BIPOC students and the challenges these students face upon entering it.

The diversity of physical geographers influences the research questions asked and the methodologies used to answer those questions, because researchers' experiences, backgrounds, perspectives, values, motivations, and identities all inform what questions they find important. The community of science frames which questions, problems, and possible solutions are important, and members of this community also determine the types of acceptable methods of investigation and how we can ascertain truth and fact [*Urban*, 2013].

Efforts to incorporate Traditional Ecological Knowledges into biogeographic research demonstrate the value of including a multiplicity of perspectives. These efforts, when collaborative rather than one-sided, can foster respectful and mutually productive partnerships with Indigenous Peoples, whereby their traditional expertise and values are integral to both the objectives and outcomes of research.

An example is the partnership of University of Minnesota and U.S. Forest Service scientists with members of the Leech Lake Band of Ojibwe. This group is developing a history of how cultural use of fire has affected "natural" forests, with a goal of "reinterpret[ing] cultural history through the development of ecological records that inform the protection, enhancement, and restoration of tribal ecocultural resources in cultural landscapes that are also multiple-use forested lands with diverse ownerships" [*Star Island Partnership*, 2021].

The current lack of diversity in physical geography reflects both a lack of awareness of the field among BIPOC students and the challenges these students face upon entering it. In this field, as in the geosciences overall, members of marginalized groups deal with ongoing stressors such as overt racism, hypervisibility, tokenism, and microaggressions [*Dutt*, 2020; *Morris*, 2021; *Shepherd*, 2020].

The culture of physical geography has historically forced BIPOC students and scientists (and those from other marginalized groups) to assimilate to the norms of the dominant group: white men. That pressure creates stress for individuals that undermines their scientific potential and personal well-being.

In addition, outside their academic settings, students from historically marginalized groups may be deterred by the demographic or cultural homogeneity or the high cost of living in the communities where many universities with graduate programs in physical geography are situated.

From a Pipeline to Pathways

Failures to diversify are often attributed to "leaky pipelines." In this conception, STEM fields lose diversity as students from marginalized groups do not move directly through bachelor and graduate degree programs into careers within their degree fields. However, the pipeline metaphor is overly simplistic, as it implies that there are definitive points of entry into higher education and only one appropriate destination: a doctorate.

The journey to becoming a scientist is rarely as linear as is implied by the notion of a pipeline. This is especially true in geography, a discipline that readily exchanges ideas with—and to which scholars often come from—corollary disciplines. Indeed, in the United States, there is no one linear track or pipeline that leads students into geography early on at the collegiate level. Recognition of this has led scholars to advocate for eliminating or replacing the pipeline metaphor in framing STEM workforce development and equity.

Geography has historically been a discipline that students serendipitously discover on their own during their undergraduate education—most often through enrolling in introductory courses to fulfill curricular breadth requirements. We need to be intentional in forging new pathways by which BIPOC students can find physical geography and achieve their desired level of education. Regardless of career end points, diversification depends on drawing in more students from marginalized groups.

That not all of these students will pursue doctorates and become professors is no failure. The failure, we contend, has lain in not doing enough to expand the pool of BIPOC students in physical geography. By increasing the numbers of BIPOC students at all levels in the field, the pool of applicants for all career paths will grow (and a representative portion of them will, if the environment is welcoming, become professors).

Below we propose a series of concerted actions for universities, departments, and professional organizations to take to increase the involvement and enrollment of students from historically marginalized groups in physical geography. Such efforts should begin by quantitatively defining the scope of the problem. However, demographic data describing the numbers of students and faculty from historically marginalized groups in physical geography are lacking. Data for geography as a whole are publicly available, but they are not partitioned between human and physical geography or by other specializations.

Geography departments should set goals for measurable improvement in recruiting and retaining students from historically marginalized groups.

We therefore urge professional organizations such as the American Association of Geographers (AAG) and AGU to help collect and make such partitioned demographic data available to researchers and their members so the extent of the diversity problem can be quantified.

Active Engagement to Expand Representation

In university and departmental settings, efforts to attract diverse students to physical geography are generally passive, limited to encouraging BIPOC students who happen to show interest, whereas active approaches are more likely to make a difference. Such

approaches include encouraging community college students and veterans (both groups that tend to be more diverse than the general student body at 4-year institutions) to transfer into the field and minimizing curricular obstacles to doing so.

We also recommend publicizing to students the relevance of climatology, biogeography, and geomorphology to tackling problems like climate change and environmental degradation so they see that they can pursue societally productive careers within the natural science realm. Further, eliminating the GRE (Graduate Record Examinations), which has been shown to be a barrier to entry for students from historically marginalized groups, as an application requirement could facilitate more diverse enrollment in graduate programs.

Geography departments should set goals for measurable improvement in recruiting and retaining students from historically marginalized groups, and they should track the numbers of new students entering physical geography specifically. These departments should also provide mentoring and support systems to help BIPOC students overcome the challenges and stressors outlined above while combating discrimination and stereotyping within undergraduate and graduate programs.

Institutions should encourage physical geographers to build outreach to marginalized groups into the "broader impacts" components of their research and grant applications. Scientists can engage local community members and students by, for example, sponsoring short-term field experiences, college camps, or summer programs on university campuses. Such outreach builds awareness of the field and can help demonstrate its relevance to environmental and social issues facing these communities.

Professional organizations such as AGU and AAG are also well positioned to facilitate recruitment and support of BIPOC students in physical geography. The AGU Bridge Program is a promising example of such facilitation, but both AGU and AAG can do more. Unlike individual institutions, these organizations can more readily operate on a national scale while helping individual departments to engage locally through initiatives like Science Olympiad, which exposes secondary students to topics connected to physical geography.

They can also participate in—or sponsor representatives from individual departments to participate in—conferences that highlight racial and ethnic diversity, such as the annual conference of the Society for the Advancement of Chicanos/Hispanics and Native Americans in Science to help raise the visibility of physical geography in those communities. Professional geosciences organizations should also seek partnerships with organizations such as the American Indian Science and Engineering Society, the Enhancing Diversity in Graduate Education program, and the Association for Women in Science to expand the visibility of physical geography to their constituents.

Professional organizations and academic departments should organize outreach efforts to institutions that do not have formal geography programs to facilitate ways to expose students at these schools to physical geography.

Institutions that primarily serve historically marginalized groups should be productive settings for exposing BIPOC students to physical geography in the classroom and field. These groups include historically Black colleges and universities (HBCUs), members of the Hispanic Association of Colleges and Universities (HACU), and Tribal Colleges and Universities (TCUs). A few HBCUs, HACUs, and TCUs have formalized geography programs (and several others have programs in environmental, atmospheric, or ecological science), but most do not.

Professional organizations and academic departments should organize outreach efforts to institutions that do not have formal geography programs (some of these institutions have individual geographers on faculty who may serve as points of contact) to facilitate ways to expose students at these schools to physical geography programs, research, and opportunities for graduate study in their regions.

Joint course offerings, field trips, and other avenues for students to meet working physical geographers are ideal ways to generate such exposure for students who otherwise may never know what the field has to offer.

The body of students earning associate degrees at 2-year colleges is more diverse than at other levels of higher education, according to recent data from the National Center for Education Statistics, so similar efforts should be made to recruit transfer students from this pool into physical geography programs at 4-year institutions.

Making a Difference for Diversity

Physical geography in the United States has traditionally been dominated by white men. The field has made little progress in diversifying, especially regarding race and ethnicity. This lack of diversity is morally problematic and detrimental to education and research in the field.

Benevolent indifference has proven insufficient to solve this problem. We therefore urge proactive targeted actions by geography departments and their host institutions as well as by professional organizations to increase diversity in physical geography.

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By **James Marshall Shepherd** (marshgeo@uga.edu), University of Georgia, Athens; **Jacob Bendix,** Department of Geography and the Environment, Syracuse University, Syracuse, N.Y.; and **Michael A. Urban,** Department of Geography, University of Missouri, Columbia

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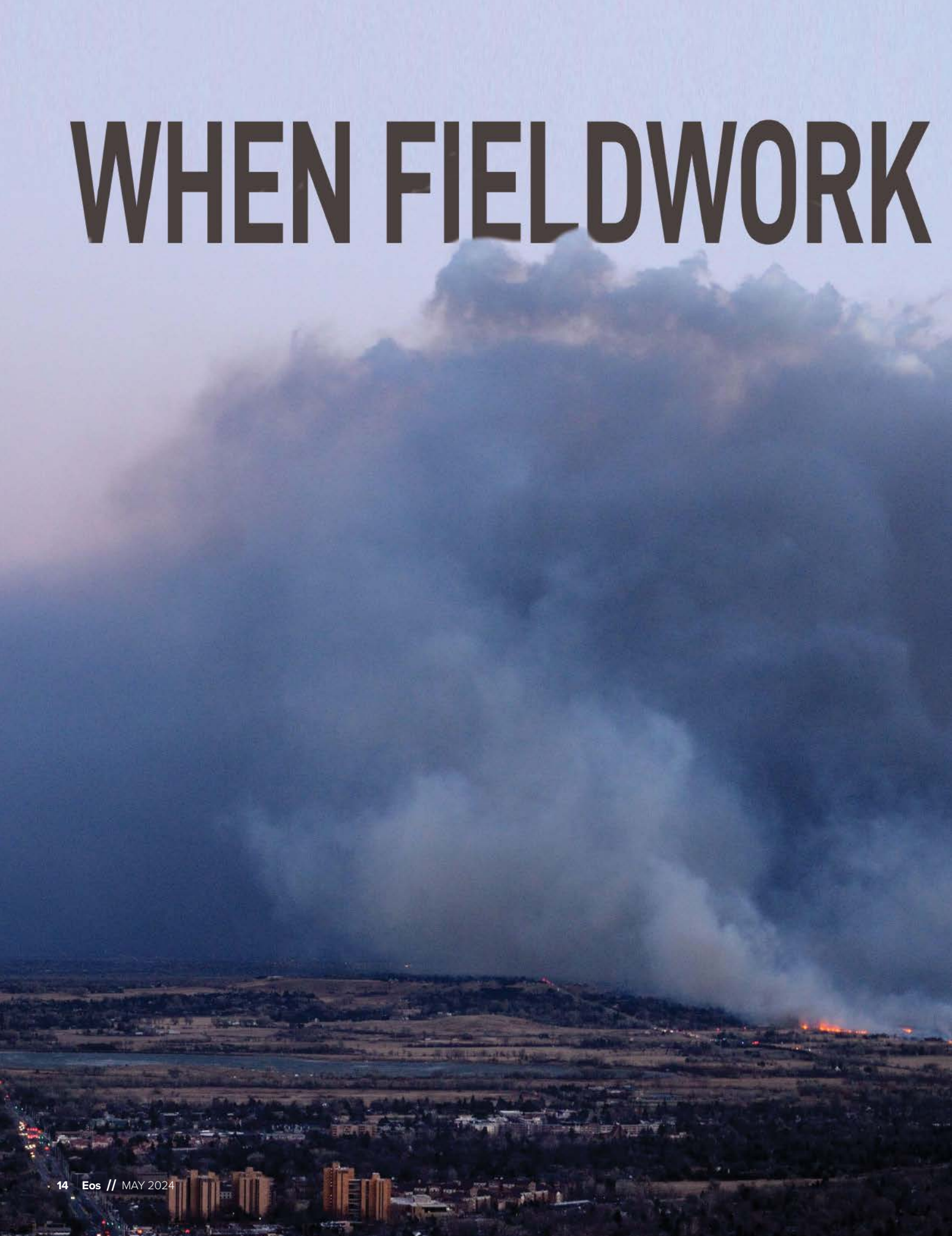
WHEN FIELDWORK



COMES HOME

By Grace van Deelen

The impacts of the 2021 Marshall Fire rippled through a community of Colorado geoscientists, spurring them to action.

On 30 December 2021, a grass fire sparked outside Boulder, Colo. Ushered in by high winds, the blaze quickly overtook homes in the towns of Superior and Louisville. Credit: Ron Rovtar Photography/Alamy Stock Photo

Opposite:

On 30 December 2021, University of Colorado Boulder (CU Boulder) glaciologist Waleed Abdalati drove from the suburbs into the city to meet one of his graduate students. As he remembers it now, the weather was foreboding: Unusually strong winds ripped through the plains abutting Colorado's Front Range. The sky was darker than it should have been. "The air was just different," he said.

Shortly into his meeting, Abdalati's teenage daughter sent him a text warning that the town of Superior—not far from their house in Louisville—was under an evacuation notice due to a fire. But six lanes of highway separated Abdalati's home from Superior. Surely the fire couldn't jump a highway like that, he thought.

Minutes later, another text from his daughter arrived, urging him to take the threat more seriously. He jumped into his car and raced home. By the time he arrived at his neighborhood, police were already blocking off the roads. Abdalati parked in a nearby condominium lot and sprinted a few hundred yards, past the police barrier, to his home, where his daughter and dog were waiting.

His daughter was upset; his dog was coughing. They ran back to the car to evacuate. Later, safe at a friend's house, Abdalati looked over a federal map of active wildfires. "It was clear that our neighborhood was not in good shape," he said.

In Superior, CU Boulder atmospheric chemist Christine Wiedinmyer was at home, working furiously on a grant proposal in her downstairs office when her phone started pinging with text messages from a colleague. Authorities had evacuated the town's Costco, a short distance from Wiedinmyer's home. She peeked outside to take a look.

Winds on 30 December were so strong that gusts blew over fences, trees, vans and more. Credit: Steven Brown

"The wind was just howling," she said. "And I could see this fire plume coming up behind my house. It was crazy." Still, Wiedinmyer felt a sense of security: She lived in the middle of a subdivision, not a forest. She headed back downstairs to work on the proposal.

Not long after that, though, an emergency text prompted Wiedinmyer and her 16-year-old son to evacuate. She grabbed her work computer, a change of clothes, car titles, and birth certificates, and they piled into the car. Looking out as they drove, they could see the extent of the destruction: Hundreds of homes had already burned.

Wiedinmyer and her son sat through an hour and a half of nerve-racking traffic, eventually arriving at her brother's house in Denver. There, they turned on the local news. "I watched three homes of people I knew just burn down on live television," she said. "It was horrifying." She went to sleep not knowing whether her house would be there in the morning.

Abdalati, Wiedinmyer, and thousands of others in the Boulder area were facing the wrath of the Marshall Fire, a blaze that would burn 2,400 hectares (6,000 acres), destroy more than 1,000 homes in 12 hours, and cause the deaths of two people.

The fire disrupted the scientific community at CU Boulder and its 950-person environmental research center, the Cooperative Institute for Research in Environmental Sciences, or CIRES, of which Abdalati is director. Finding a void in reputable information available to their concerned neighbors, many of the scientists became go-to resources and quickly assembled to answer lingering questions about the effects of urban fires.

Fanning the Flames

Colleen Reid, a geographer at CU Boulder, was visiting family on the East Coast on the day of the fire. Her home, 3 kilometers (2 miles) north of the fire, was not affected. As she drove from one relative's house to another back East, she fielded messages from friends who were being evacuated in Boulder.

The fire took everyone by surprise, she said. Most fires that happen in the Front Range start west of Boulder in the foothills, pouring smoke into the city and farther east.

But unusual conditions that year disrupted that pattern, she said.

The spring had been very wet, spurring lots of plant growth. The following summer and fall, though, were unusually dry, turning all that extra vegetation into fuel. Until the day after the fire, there hadn't been snow cover in the area, either, which would have slowed the flames.

In addition, a record-breaking windstorm had started the morning of the fire. Winds picked up as the day went on; gusts of up to 185 kilometers (115 miles) per hour blasted across the landscape. The windstorm and vegetation conditions set the stage for two sparks—one from a power line and another from a trash fire—to start the blaze.

Shortly after 2:00 p.m., strong winds carried the fire across the Denver–Boulder Turnpike, the six-lane highway separating Abdalati's neighborhood from the fire's origins. Winds didn't weaken until 7:30 that evening.

Confusion in the Community

The morning after the fire, Abdalati returned to his neighborhood to find his entire block obliterated except for two houses: a neighbor's and his own.

"YOU START TO WONDER, HOW BAD IS THE AIR? HOW BAD IS THE SOIL? WHAT ARE WE REALLY DEALING WITH HERE?"

Some houses in Superior and Louisville burned to the ground, whereas others were spared. Credit: Bmurphy380/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

"It was hard to see," he said. "I was watching neighbors come home to find everything destroyed. It was just heartbreaking."

Abdalati's house smelled strongly of smoke, and it badly needed remediation. He and his family moved into a friend's empty condo nearby. It was a frustrating time for the family, who suddenly had no belongings. "You just get really antsy to go home," he said.

But moving back home came with its own anxieties. "You start to wonder, How bad is the air? How bad is the soil? What are we really dealing with here?" Abdalati said. At the recommendation of the insurance company, the family replaced all the cloth furniture and carpeting. It was more than 4 months until the remodel was complete.

Wiedinmyer's home also smelled of smoke when she and her son returned. Black ash coated the interior windowsills and doorways. She did most of the cleanup herself, changing the air filters in her HVAC (heating, ventilation, and air-conditioning) system, wiping down all surfaces with soapy water, airing out the house for days, and vacuuming upholstered furniture.

Alongside gratitude that her home was still standing, Wiedinmyer was frustrated at the many professional cleaning companies that descended upon the neighborhood offering various services not necessarily backed by science. "They were scaring people," she said.

As an atmospheric chemist, Wiedinmyer was able to test the air quality of neighbors' homes. She remembered measuring air quality inside a house that had been heavily affected by smoke when a cleaning company arrived. To Wiedinmyer's surprise, the cleaners, working without any personal protective equipment, fired up a dust vacuum. "That just sweeps up [dust] and pours it into the air," she said.

Cleaners were also providing air quality testing services using opaque methods and offering opaque results. "It was really hard to get value out of the data collected or really understand how meaningful they were," she said.

Facing muddled recommendations from cleaning and insurance companies, Wiedinmyer's neighbors had plenty of questions. "I had friends within a day asking, What are we smelling? Is this safe? What's in our houses? You're the scientist, you're the air quality person," she said. "I was like, You know, I don't know."

Wiedinmyer remembered calls with neighbors in which she described her own cleaning protocol and explained the possible risks and unknowns—of which, she realized, there were many.

Studying the air quality impacts of fires requires having a good idea of the materials that burned. With wildland fires, that's relatively easy, as most of the burned material is vegetation. But in this

"THESE PEOPLE HAD QUESTIONS, AND IT WAS HARD TO GET SOMEONE TO TALK TO. AND THEN SUDDENLY WE WERE THERE, AND THEY COULD TELL THEIR STORY."

urban fire, almost anything could have burned, releasing an array of unknown chemicals.

The peak temperature of the fire was nearly 1,400°C (2,500°F), so everything, including the frames and batteries of cars, burned. In a fire, burned materials release metals, molecules called polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs), some of which are carcinogenic. Urban structures release more PAHs than vegetation does, and research shows that levels of PAHs after fires are higher indoors than outdoors.

"You can only imagine all the toxics that are around," Wiedinmyer said.

And with thousands of chemicals possibly burned in the Marshall Fire, scientists were far from fully understanding the air quality impacts. It was challenging, Wiedinmyer said, to act as a resource for neighbors when the science itself was so lacking. "I appreciated being able to have more information than others could get, but there were a lot of unknowns," she said.

Scientists Step Up

Joost de Gouw, an atmospheric chemist at CIRES, also remembered the day of the Marshall Fire starting with foreboding winds. He returned home early from a walk with his dog because he didn't feel safe in the record-breaking gusts. The winds, luckily, were blowing the fire away from de Gouw's home.

He was never evacuated but spent the day glued to the news and watching as gusts toppled his fence and tree branches flew through the air. He could see the fire raging from his window.

"It was very traumatic for our community," he said.

In the days after the fire, de Gouw joined Wiedinmyer, Reid, and other CU Boulder and CIRES air quality and health scientists in an email chain, sharing resources on wildfires, air quality, and safety. That email chain turned into a Google Doc, which was shared on the CIRES website. When approached with questions, the scientists could point their neighbors to this crowdsourced page.

"Here we were with all this expertise—I felt an obligation to our community to collect information and data that would be helpful to people," Wiedinmyer said. But the science on indoor air quality impacts was still frustratingly incomplete.

Some homes that did not burn were filled with soot from the fire. Credit: Joost de Gouw

De Gouw realized that the fire offered an opportunity to begin filling some of the gaps in scientific knowledge of urban fires. That gap is twofold, he said: "First, what chemicals do you get when you burn stuff? And second, what are the health effects of those chemicals?"

At first, he wondered whether doing research in the wake of such a disaster was right. He worried that adding a team of researchers to the chaos would compound the stress faced by the suffering community. But after realizing people had questions that he knew CIRES scientists could answer, his thinking shifted, and he got to work.

De Gouw and a team of researchers placed low-cost air quality sensors in 12 homes that had been affected by smoke and ash. In one of the most heavily affected homes in Superior, they placed a higher-resolution instrument, a mass spectrometer that could measure the concentrations of indoor gases, including VOCs, as well as another sensor that measured particulate matter in the air. The instruments collected data for 5 weeks.

The team "jumped right on it and just sort of thought, We'll figure out how to pay for this later," Abdalati said. As director, he was proud to see how CIRES researchers mobilized quickly to serve their community, even as some of them were dealing with the aftermath of the fire themselves.

A local mass spectrometer manufacturer, Tofwerk, loaned the team a smaller mass spectrometer that could be wheeled from house to house to make measurements. Residents watched in real time as the data on the air in their homes came in.

It wasn't hard to find research sites; more community members offered up their homes than de Gouw's team had the resources to test.

Abdalati's home was one of those instrumented. He remembered watching a graph in real time as de Gouw measured concentrations of benzene, a cancer-causing VOC that results from burning urban materials. Standing outside the house, de Gouw slid the benzene sensor through the window. Immediately, the graph shot up. "Clearly, we were way over safe levels," Abdalati said.

As a scientist in people's homes, de Gouw saw the aftermath of rapid evacuations and listened to scores of stories about the day of the fire. Some of them were harrowing, of people rushing through burning neighborhoods to save children or pets. Residents spoke of the trauma of continuing to live in neighborhoods that were now destroyed. "Some homes, if you look out the front door, all you'd see is destruction," de Gouw said.

Disaster response was an aspect of research de Gouw hadn't dealt with before and found hard to navigate. But the response from residents was entirely positive. De Gouw realized that the work his team was doing was meaningful both scientifically and emotionally, and it had therapeutic value.

"These people had questions, and it was hard to get someone to talk to. And then suddenly we were there, and they could tell their story," he said. "That felt good."

The data showed that most air pollutants dissipated after about 6 weeks. However, VOCs—more than 500 types of which were present in affected homes that weren't detected in outdoor air—remained in the smoke-affected homes for several additional weeks. That's much longer than expected, according to de Gouw.

The team also found that the professional cleaning services consulted didn't sufficiently fix air quality problems and that indoor cleaning actually increased the concentration of harmful particles in

the air by resuspending ash and soot. The scientists are currently conducting a new laboratory experiment in which they're burning common household goods and measuring the chemicals emitted; they hope the results will further identify which chemicals may be present after urban fires like the one that struck Boulder.

Reid is studying the long-term health effects associated with the fire via a multiyear survey of affected residents. Some people, she said, have reported developing rashes when they enter their homes or persistent headaches that subside only when they're away. Symptoms vary on the basis of people's sensitivities and the location of their homes, she said.

She and her colleagues still don't have enough evidence to draw conclusions about the extent of the health effects in the community.

Reid said that the fire opened her eyes to the gaps that exist in scientists' knowledge of indoor air quality after urban fires, especially the health impacts of VOCs. "We have not been paying enough attention," she said.

Researchers installed instruments in a home in Superior that was affected by wildfire smoke to measure what chemicals were in the air. Credit: Joost de Gouw

Climate Change Hits Home

The fire and its aftermath imparted a new sense of community accountability in the scientists. For Abdalati, the fire was the first time he had lived through a climate change–related disaster like those he teaches about.

"It's one thing to talk about climate change in an academic sense," he said. "It's very different to live it."

As global temperatures climb, fire frequency and intensity are on the rise—as is the number of people affected by fires. "My experience is just one that many will have," Abdalati said. "We're perturbing the system in ways that have really large ramifications."

As more urban fires occur and more people face their effects, understanding the extent of the chemicals those fires release and the health impacts of those chemicals—as CU Boulder scientists are working to do—will become more and more important, Wiedinmyer said.

Increasingly common, urban fires will bring more scientists into closer contact with those affected by tragedy. When speaking with affected homeowners and renters, de Gouw and his team learned that patience, taking community members' concerns seriously, and listening intently were key to building good research relationships.

They also learned that close contact with communities can make for powerful science. "This was really, for me, the first case where the science was so intimately involved with the community," de Gouw said. "It definitely changed my perspective."

De Gouw said he especially appreciated the shared desire of scientists and community members to thoroughly understand what was happening inside their homes—a common goal he hadn't experienced in previous air quality research. Questions from affected community members guided the scientists' research.

As community members offer up interesting research questions, scientists must respond, said Wiedinmyer. The aftermath of the fire made her realize the importance of considering her audience and sharing information that community members can actually apply to their own lives. A community in distress probably doesn't care about her wildfire modeling work, for example, she said. But she still holds expertise to answer questions related to the disaster at hand.

"How can I provide resources that are directly useful?" she asked.

Learning how to celebrate research successes and respect the tragic nature of the event was difficult too. De Gouw's team, for example, won awards from Boulder County, the state of Colorado, and the Denver Museum of Nature and Science for the work they completed after the fire. When accepting the awards, de Gouw made sure to commemorate those who lost the most.

More than 2 years later, Wiedinmyer still gets calls and emails from community members with questions about the safety of their homes. Many residents on the Hawaiian island of Maui reached out to Wiedinmyer too, after urban fires devastated the city of Lahaina in August 2023. As a result, she and other CIRES scientists plan to update their collection of resources and create a manual for the next time a large urban fire happens.

"If a scientist has information to benefit the community, I think there is an obligation to share it with the community," Abdalati said. "We're in it together."

Author Information

Grace van Deelen (@GVD__), Staff Writer

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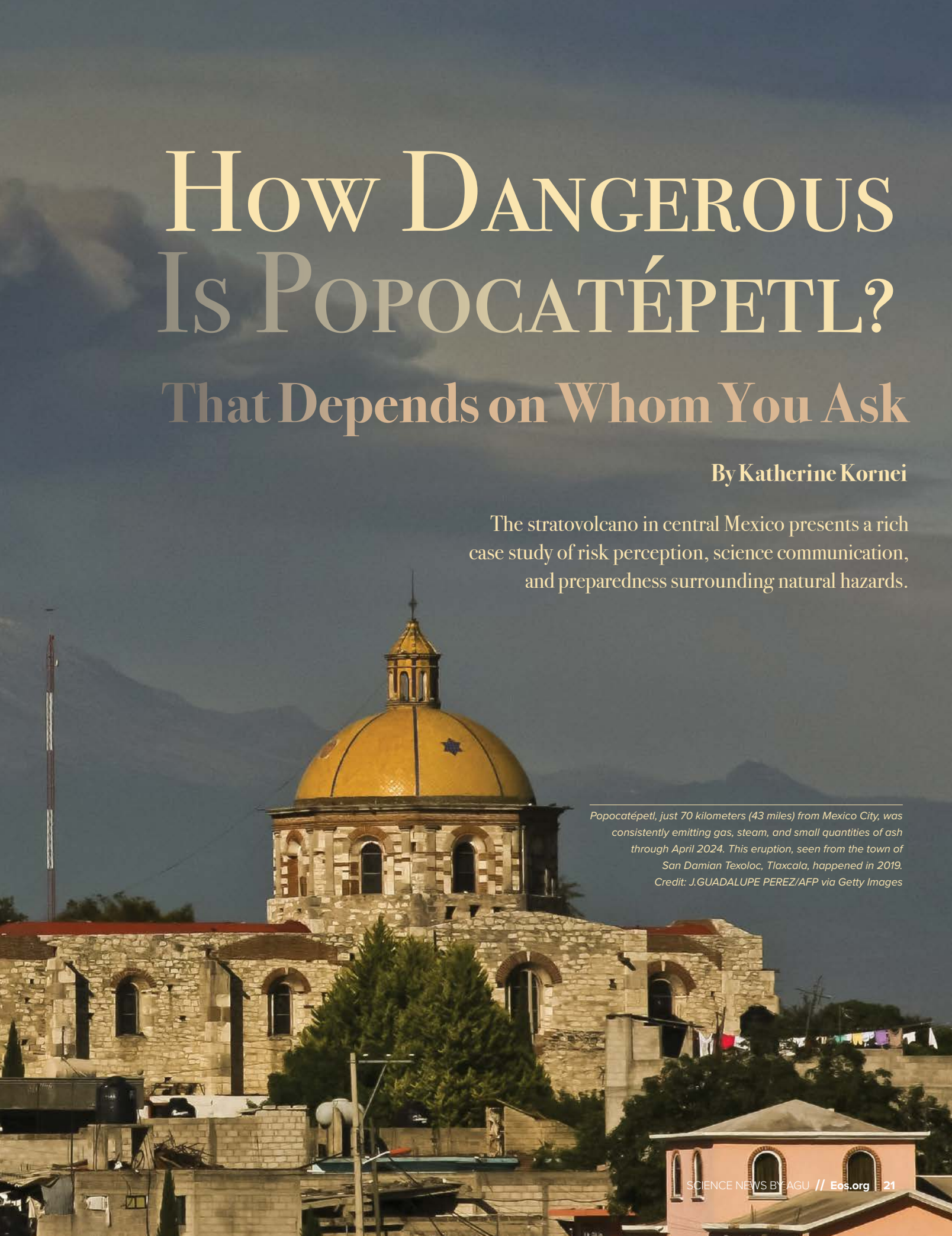
How Dangerous Is Popocatépetl?

That Depends on Whom You Ask

By Katherine Kornei

The stratovolcano in central Mexico presents a rich case study of risk perception, science communication, and preparedness surrounding natural hazards.



Popocatépetl, just 70 kilometers (43 miles) from Mexico City, was consistently emitting gas, steam, and small quantities of ash through April 2024. This eruption, seen from the town of San Damian Texoloc, Tlaxcala, happened in 2019. Credit: J.GUADALUPE PEREZ/AFP via Getty Images

If headlines are to be believed, the 22 million people living in the greater metropolitan area of Mexico City are in danger. The menace is Popocatépetl, a volcano that rumbled to life in 1994 after decades of quiescence. Reports frequently use words and phrases like "threatening" and "booming eruptions" to describe the active stratovolcano 70 kilometers southeast of Mexico's capital.

The real story is much more nuanced, of course—Popocatépetl poses varying levels of hazards, and people's views about volcanic activity are framed by their life experiences, their own perceptions of risk, and the communication efforts of scientists and government officials.

Popocatépetl is perhaps the best-known feature of the Trans-Mexican Volcanic Belt, which extends more than 600 kilometers across central Mexico. The 5,400-meter-high stratovolcano can be seen from several cities and towns, and it features prominently in Aztec legends as well as in the religious beliefs of many contemporary Mexicans, particularly those living in rural communities. Since the mid-1990s, Popocatépetl has become more active and has been a fixture in the news and social media.

"It's one of the most active volcanoes in Mexico," said Lizeth Caballero García, a volcanologist at the Universidad Nacional Autónoma de México in Mexico City. "It's considered the riskiest."

Popocatépetl looms over central Mexico, but local perception of risk varies depending on such factors as age, proximity, and life experience. Credit: Russ Bowling/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Active Across the Ages

Popocatépetl has a long history of activity: A research team led by Sapienza Università di Roma geologist Ivan Sunyé Puchol recently estimated that the volcano has erupted explosively more than 25 times over the past 500,000 years. Sunyé Puchol and his collaborators reconstructed the past activity of Popocatépetl and other volcanoes by dating layers of pumice. The Popocatépetl pumice that the researchers studied was birthed in sizable eruptions, events with a volcanic explosivity index (VEI) in the range of 4–6, the team has suggested. (For comparison, the 18 May 1980 eruption of Mount St. Helens in Washington state had a VEI of 5.)

Popocatépetl's last explosive eruption of significant size occurred roughly 1,100 years ago. However, the volcano rumbled to life again in late 1994 with a series of small eruptions (maximum VEI of 2) that produced a 7-kilometer-high column of ash.

> "It's one of the most active volcanoes in Mexico."

Popocatépetl has remained active since then, and light brown ash has repeatedly dusted nearby towns like Tetela del Volcán, Morelos, and even more distant municipalities like Puebla and Mexico City. Mudflows of pumice and ash known as lahars have coursed down the volcano's nearly vertical slopes. Pyroclastic density currents—clouds of hot gas and volcanic debris that race downslope at hundreds of kilometers per hour—have also been reported at Popocatépetl.

"Ashfalls, lahars, and pyroclastic density currents are, in my opinion, the real hazards today," said Sunyé Puchol.

The Cloud and the Governor

But accurately and effectively communicating the various risks posed by Popocatépetl is challenging work. For example, a phenomenon that outwardly appears to be dangerous—an ash cloud towering high in the atmosphere, for instance—might, in fact, pose little risk to nearby populations.

Ana Lillian Martin del Pozzo, a volcanologist also at the Universidad Nacional Autónoma de México, remembered a government official calling her late one night to ask for advice. The state governor was worried because he had seen a big black cloud in the sky, and he was considering issuing an evacuation order. That's just ash, Martin del Pozzo assured him, and it wasn't cause for evacuation. But if that ash starts falling to the ground, she added, residents should take precautions like staying indoors whenever possible

and covering their faces when going outside.

Advice like that makes sense to most people, said Martin del Pozzo, because the public generally has a good understanding that inhaling particulate matter can be harmful to the respiratory system (never mind that volcanic ash bears no resemblance to the ash produced by a fire).

However, there's another deleterious effect of ash exposure that's much less well-known, she said: "It's on the eyes." Volcanic ash, which is composed of bits of glass and rock, can abrade the delicate tissues of the ocular system. Symptoms such as redness, itching, and discharge are common, researchers found when they studied people living near an active volcano in Japan.

People who live in the shadow of Popocatépetl should take a few simple steps to protect their eyes when ash is falling, said Martin del Pozzo. "Wear glasses. Wear a hat."

The Shadow of Don Goyo

Not everyone heeds those warnings, however.

When Caballero García visited Hueyapan, for instance, a small town in the state of Morelos, she heard stories of local women purposely going outside when ash was falling. They knew that the material came from Popocatépetl, a mountain they viewed as being imbued with spiritual power, and were trying to collect ash on their heads, said Caballero García. The women were mainly driven by curiosity, she said, but it's important to remember that to many Mexicans, Popocatépetl is more than just a volcano.

"Popocatépetl is considered in some towns to be a sacred mountain, with a complex identity between god and human," Caballero García said.

Popocatépetl appears in Aztec legends, and small towns near the volcano typically feature murals showing Popocatépetl in two forms: the volcanic edifice and an Aztec warrior known as "Don Goyo," a generally benevolent personification of the volcano, also associated with Saint Gregory. Either way, "Popo has a human name," said Caballero García. Every year on 12 March, the saint's day, people hike up the volcano's flanks to leave offerings of food and flowers.

That duality—Popocatépetl the physical volcano and its spiritual likeness—affects how people conceptualize volcanic risk, which is itself shaped by life experiences and personal beliefs, among other factors.

Between 2013 and 2016, a team of researchers interviewed more than 130 residents of Tetela del Volcán, a town located just 15 kilometers from Popocatépetl's crater, to better understand local risk perceptions surrounding Popocatépetl. Some of the participants were young enough that they had grown up knowing the volcano only in its current active phase; others remembered an earlier time when Popocatépetl was dormant.

The researchers found that older adults tended to harbor more symbolic beliefs about Popocatépetl and its personified form of Don Goyo. "The elderly have more conceptions of respect and symbolism with respect to the volcano," said Esperanza López-Vázquez, a social and environmental psychologist at the Universidad Autónoma del Estado de Morelos in Cuernavaca, Mexico, and a member of the research team. Those beliefs correlated with lower perceptions of risk, the team found.

On the other hand, the research revealed that adolescents and middle-aged adults tended to base their impressions of Popocatépetl–related risks more on scientific information. Accordingly, younger people had a greater perception of risk, said López-Vázquez, despite learning about Popocatépetl from the oral histories of their elders.

> "Popocatépetl is considered in some towns to be a sacred mountain, with a complex identity between god and human."

These differences in perceived risk, she said, can "generate tensions between generations."

Both middle-aged and older adults remembered being urged to evacuate Tetela del Volcán in 2000 and 2001 because of increased volcanic activity. Poor road conditions made mass evacuations difficult, resi-

A signpost points the way for residents to evacuate as a small plume vents from Popocatépetl in the distance on 8 November 2000. Credit: REUTERS/Daniel Aguilar

dents recalled, and there were underlying feelings of unease and distrust about leaving belongings and farm animals behind. It's natural that those life experiences might affect someone's decision to evacuate again in the future, researchers concluded.

Young people had never experienced a Popocatépetl–related evacuation but had grown up hearing and feeling the volcano's rumblings, the team reported. "At the same time you are afraid, but it is something normal, which we are used to," one young participant said.

"People have learned to live with the risk of the volcano," said López-Vázquez.

In light of those varied coping strategies, scientists and policymakers have found that it can be difficult to balance the need for public safety with respect for personal beliefs. Mexican officials have tended to err on the side of providing recommendations to avoid particularly risky areas rather than banning access to Popocatépetl entirely, for instance. (People are legally prevented from living within 12 kilometers of the volcano, however.)

> "Science is not finished until you explain it to everyone."

Balancing Safety and Personal Beliefs

The residents of Tetela del Volcán clearly differ in their perceptions of volcanic risk, and they use a wide range of strategies to cope with the presence of an active volcano. Those strategies include everything from personifying the volcano as a benevolent being, to believing that a dearth of recent disasters confers immunity from future hazards, to developing a strong community identity that views relocation as an act of abandonment.

Helping people feel empowered is an important aspect of disaster preparedness. From ShakeAlert messages that provide warnings to drop and cover before an impending earthquake to signs posted in coastal areas indicating tsunami evacuation routes, providing information in advance allows people to prepare and therefore feel more capable and confident when a disaster does strike.

In 1997, Mexico's National Center for Disaster Prevention (CENAPRED) unveiled the first version of a hazards map for Popocatépetl (bit.ly/Eos-Popo). That map, which was updated again in 2016, indicates regions most likely to be affected by ashfall, lahars, pyroclastic density currents, and lava flows, among other volcanic risks.

The Popocatépetl hazards map is published online in both Spanish and the local Nahuatl language, and it's regularly publicized via social media, Tomás Alberto Sánchez Pérez, CENAPRED's director of communications, said.

But just because a resource is online doesn't mean that everyone is seeing it. That's particularly true because Internet access isn't a given across all of Mexico. Urban centers like Puebla and Mexico City have plenty of connectivity, but many small communities aren't as digitally equipped, said Sunyé Puchol, who lived near Mexico City from 2012 to 2018. "There are two worlds in Mexico," he said.

The digital divide between urban and rural populations means that scientists and government officials alike must rely on multiple methods for communicating volcanic risks. The most tried and true involve making face-to-face connections.

Connecting in Person

Martin del Pozzo and her collaborators often bring physical copies of the Popocatépetl hazards map into schools and universities. "We've been doing that kind of in-person outreach for decades," she said. "We began working with the people before Popo started erupting."

Martin del Pozzo has watched students grow up, and she's developed a rapport with educators who invite her back year after year.

Sunyé Puchol and other researchers have also visited numerous communities near Popocatépetl.

In the wake of a magnitude 7.1 earthquake that struck central Mexico in 2017, Sunyé Puchol and other volunteers traveled to several small towns to provide relief supplies and talk with community members about the risks posed by natural hazards like earthquakes and volcanoes. The earthquake itself had killed hundreds of people, and the ground shaking had also triggered several lahars on Popocatépetl. Sunyé Puchol and his colleagues emphasized that sometimes an unrelated hazard—in this case, an earthquake—can affect volcanic risks.

Many highly technical scientific data—including measurements of ground deformation, volcanic tremors, and gas emissions, for example—go into predicting Popocaté-

petl's risks. But most of those measurements won't make much sense to the average person, said Sunyé Puchol. It's critical to distill that information into concepts that are understandable to nonscientists, he stressed. "Science is not finished until you explain it to everyone."

Red, Yellow, Green

With the goal of facilitating clear communication about Popocatépetl, in 1998 the Mexican National Civil Protection System unveiled an alert system modeled on the familiar colors of a traffic light. The lowest level of the Volcanic Traffic Light Alert System is green and corresponds to very little or no risk. The next level, yellow, indicates a state of alert, and it's divided into three phases. The highest level, red, means that evacuation might be imminent. Since its inception, the Volcanic Traffic Light Alert System has mostly toggled between the second and third phases of the yellow level.

"We're hardly ever in green," said Martin del Pozzo.

Such systems are effective at conveying risk quickly in an intuitive way, said Simon Carn, a volcanologist at Michigan Technological University in Houghton. "Most people use these kinds of systems in order to avoid being too quantitative."

Similar color-based systems are in widespread use (for indicating fire danger, for example). However, there is a downside to simplifying the inner workings of the Volcanic Traffic Light Alert System for the public. People were initially skeptical about why the levels of the alert system kept changing, said Martin del Pozzo. That was especially true for populations that lived farther away from the volcano and were therefore more isolated from its impacts. But those communities are not immune: Ash from Popocatépetl has fallen on relatively distant Mexico City more than 19 times since 1994, and schools and airports in the region have occasionally been shuttered in response, most recently in May 2023.

Between 2020 and 2021, Caballero García and Edwin Hazel López Ortíz, an Earth scientist also at the Universidad Nacional Autónoma de México, surveyed more than 4,800 people living in Mexico City. They queried the respondents, who ranged in age from 12 to 99, about their scientific understanding of volcanic ash, their recollections of prior Popocatépetl ashfall events, their awareness of measures to protect themselves from falling ash, and their feelings surrounding ashfall events.

Following decades of quiescence, Popocatépetl has been more active since the mid-1990s. Seen here from the town of Santiago Xalizintia, steam and ash stream from the volcano on 12 May 2023. Credit: REUTERS/Imelda Medina

The team noted that although most people knew what volcanic ash was and how it was produced, they were largely unaware of how to protect themselves from it. For example, nearly 90% of people aged 12–24 did not know what to do in the event of ashfall, Caballero García and López Ortíz found.

Because younger people tended to seek out news about Popocatépetl predominantly from social media, the team emphasized the importance of sharing protective measures related to ashfall on social media platforms.

Experiencing an ashfall event furthermore triggered a wide range of emotional responses, Caballero García and López Ortíz found. Respondents commonly reported feelings of peril, indifference, interest, fear, and surprise.

For participants old enough to have experienced an ashfall event in the past, a fresh dusting of ash was also an opportunity for a teaching moment. It allowed people who are parents, said Caballero García, to tell their children about Popocatépetl and how to remain safe.

The researchers found that individuals who remembered an ashfall event were more likely to believe that ash could once again blanket their home or place of work. People who were aware of Popocatépetl's hazards map were more likely to feel prepared in the event of falling ash, Caballero García and López Ortíz reported at AGU's Fall Meeting 2021 (bit.ly/AGU21-Popo).

Recognizing Risk

Like other natural hazards, volcanoes clearly manifest their risks in complicated ways.

"We can't predict eruptions very accurately," said Carn. Moreover, he continued, events like falling ash can be affected by other phenomena that are themselves unpredictable. For instance, "ashfall depends on where the wind is blowing," he said. "That adds further uncertainty."

In the face of all that ambiguity, what's a person to do? López-Vázquez maintained that no one particular mindset is healthiest when it comes to internalizing volcanic risks. Instead, she said, the key is acknowledging that there is always some level of risk associated with living near a volcano like Popocatépetl. "The most important thing is not to deny that it exists."

Author Information

Katherine Kornei (@KatherineKornei), Science Writer

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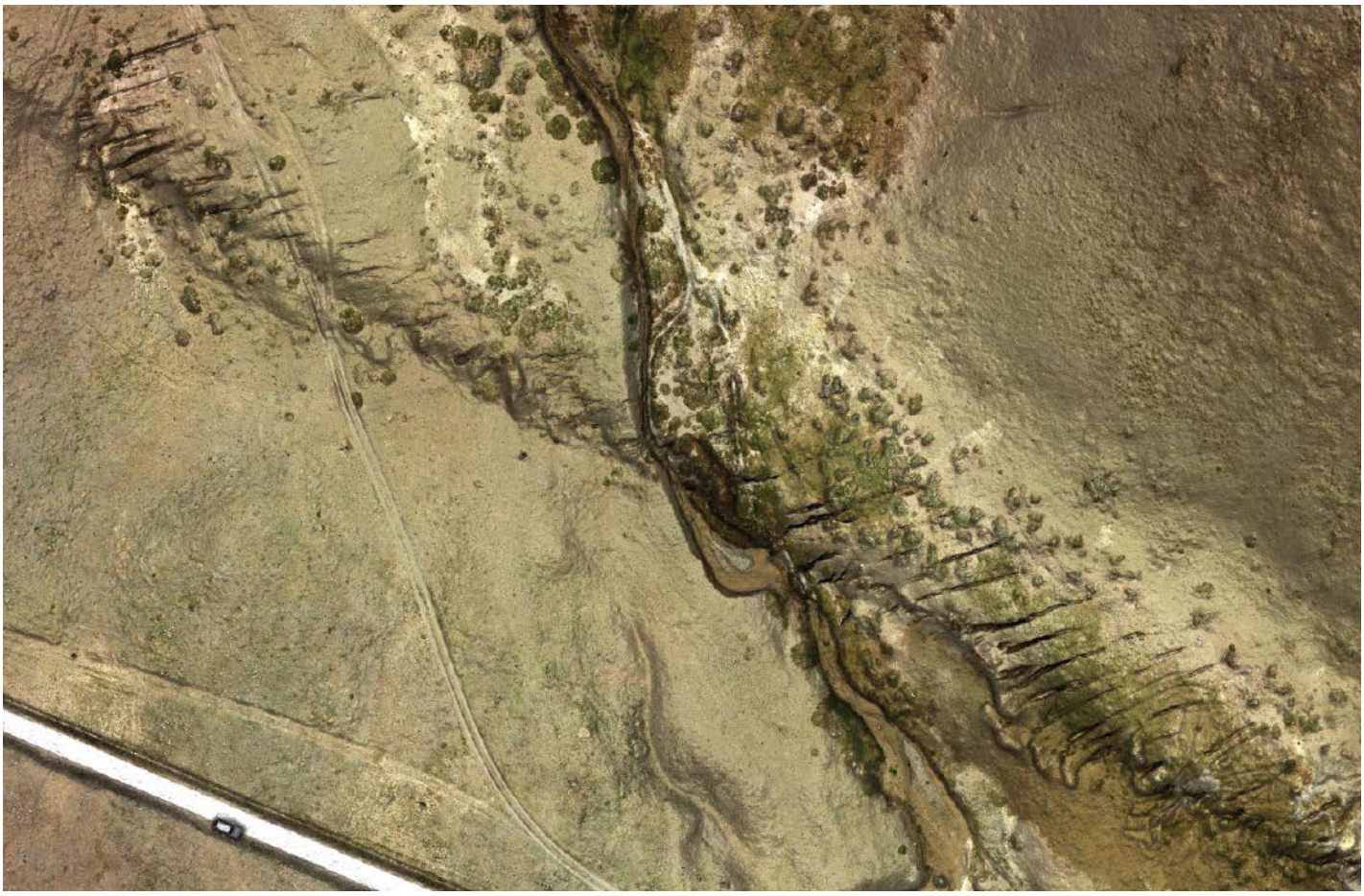
Fault Maturity or Orientation: Which Matters More for Quakes?



Researchers used unmanned aerial vehicle images superimposed on centimeter-resolution topography to study the surface rupture of the 2021 magnitude 7.4 Maduo earthquake in China. This image shows the fault scarp, tensional cracks on the hanging wall, and the left-laterally offset channel. Credit: Yanxiu Shao

In the early morning of 22 May 2021, a magnitude 7.4 quake rattled China's remote Maduo County on the Tibetan Plateau. It was the most recent in a series of nine earthquakes with a magnitude of 7 or greater since 1997, and its surface rupture was twice as long as the global average for similarly sized quakes. The tremor occurred on the eastern part of the relatively immature left-lateral Jiangcuo fault system, which slips slowly, about 1 millimeter per year, and was unmapped before the quake.

Uncovering the geological dynamics of this disaster could help inform future efforts to assess seismic hazards in the region and around the world. In a new report, *Liu-Zeng et al.* analyze the Maduo quake to probe the relationship between fault structure and earthquake dynamics.

To do so, the researchers combined field observations with satellite images taken prequake and postquake as well as with centimeter-resolution photos taken of the fault system by an unmanned aerial vehicle. These remote sensing techniques enabled them to analyze fractures that would otherwise be inaccessible because of their high altitude and harsh surrounding environment.

The research team assessed changes to Earth's surface both on and near the fault segments involved in the quake. The segments had varying orientations with respect to the overall regional patterns of seismic stress, as well as varying degrees of maturity. Maturity is not necessarily synonymous with age; rather, it indicates the degree of a segment's development, or how much it has changed with time and activity.

Prior research has highlighted the importance of fault maturity in earthquake dynamics. However, in the case of the Maduo quake, the researchers found that the faults' orientations played a larger role in the magnitude and the degree of localization of surface deformation than their maturity levels. These findings suggest that future seismic hazard assessments might be enhanced by more thoroughly accounting for fault segment orientation in the context of regional stress conditions. (*AGU Advances*, https://doi.org/10.1029/2023AV001134, 2024)

—Sarah Stanley, *Science Writer*

Urban Nature Is Often Plentiful but Inaccessible

Living near parks, trees, streams, coastlines, and other green and blue natural features may promote physical and mental well-being.

With those benefits in mind, dozens of mayors from the C40 Cities Climate Leadership Group, which includes urban areas from Seattle to São Paulo, Stockholm to Shanghai, signed the Urban Nature Declaration in 2021. In it, they agreed to work toward two goals: covering at least 30% of each city's total area with green space and ensuring that no less than 70% of its population can access nearby green and blue spaces within 15 minutes—all by 2030.

Now, research by *Martin et al.* suggests that most of the 96 C40 cities, not just the 31 declaration signatories, have achieved the green space coverage goal, but fewer than half have achieved the accessibility target.

Many studies of green space and related health outcomes use the normalized difference vegetation index, which relies on remotely sensed measurements of visible and near-infrared light to determine vegetation density. However, this metric does not capture the accessibility, usability, or category of green spaces. And there is no standardized measurement metric for blue spaces.

So to evaluate the cities' progress, the researchers developed a new analytical framework that uses satellite imagery from the European Space Agency's WorldCover and Sentinel-2A data sets to determine the coverage area and location of natural spaces within each city. This framework allowed them to use multiple metrics for tracking each city's progress toward the Urban Nature Declaration targets.

They found that 80% of the 96 cities have achieved at least 30% green space coverage, but only 47% of the cities have natural spaces that are easily accessible to at least 70% of people living there. In some cities, natural spaces are highly concentrated, whereas in others the spaces are more dispersed.

The researchers also developed a method for translating the two goals into a metric used in many epidemiological studies. In the future, this metric will help them investigate the health benefits of expanding natural space in cities. (*GeoHealth*, https://doi.org/10.1029/2023GH000996, 2024) **—Sarah Stanley,** *Science Writer*

Researchers Develop Mexico's First Comprehensive Greenhouse Gas Budget

Fossil fuel burning is the biggest source of greenhouse gas emissions in Mexico. Credit: Curt Carnemark, World Bank Photo Collection/Flickr, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Mexico's greenhouse gas emissions are the second highest among Latin American countries, trailing only Brazil, according to the World Bank. But until now, no one had leveraged the full spectrum of available scientific data to make an estimate of sources (such as fossil fuel burning and agriculture) and sinks (such as healthy forests and soils) of carbon dioxide, methane, and nitrous oxide. Calculating the country's greenhouse gas budget could help policymakers develop effective emissions reduction strategies.

Murray-Tortarolo et al. calculated Mexico's first comprehensive greenhouse gas budget based on estimates from multiple data sources of greenhouse gas fluxes in the country between 2000 and 2019.

The researchers used data from the Regional Carbon Cycle Assessment and Processes Phase 2, official national budgets, and several other scientific reports and studies in their analysis. They found that different data sources broadly told the same story about anthropogenic greenhouse gas emissions from sources including fossil fuel burning and agriculture. However, there were discrepancies when it came to natural emissions sources such as wetlands and natural sinks such as forests and soils. In particular, the team found that studies may overestimate the role that land ecosystems play in removing carbon from the atmosphere.

The analysis comes at a particularly important time for Mexico, which recently reported an increase in greenhouse gas emissions after more than a decade of reductions. The researchers note that limited data exist about considerations such as the role of aquatic systems and methane consumption by soil but suggest that their findings can help guide future scientific research and enable lawmakers to target the greatest sources of emissions. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2023JG007667, 2024) **—Rachel Fritts,** *Science Writer*

Anzali Wetland, Iran's "Ecological Gem," May Dry Up by 2060

As climate change progresses, the world's wetlands are disappearing, more quickly in some places than others. Iran has the second-fastest rate of wetland loss (after Greece), having lost 14% of its wetland area between 2010 and 2020.

The Anzali wetland sits in northern Iran, where nine major rivers meet the Caspian Sea. The wetland, one of the world's largest freshwater lagoons, hosts at least 150 species of resident and migratory birds; 49 species of fish; and a multitude of mammals, amphibians, and reptiles. It helps drive the local fishing and agriculture economies and draws more than 180,000 visitors each year.

But because of higher sediment loads, increased water demands, a warmer and drier climate, and lower water levels in the Caspian Sea, the wetland shrank from 258 square kilometers (100 square miles) in 1930 to just 52 square kilometers (20 square miles) in 1989, losing about 80% of its water surface area in the process. Degradation continued after that point, and today, scientists are concerned that the wetland could disappear altogether.

Mahdian et al. modeled the wetland's potential futures with different climatic, hydrologic, and anthropogenic trajectories for the rest of the century. Over that period, the Caspian Sea's water level is projected to drop by 4–10 meters (14–33 feet). The modeling found that in more extreme scenarios, the Anzali wetland could dry up entirely by about 2060. Even in the most conservative scenarios, the wetland will become only a seasonal water body by the end of the century, which would still negatively affect the region's ecology and economy.

The consequences of desiccation are dire, ranging from a decimated economy due to declines in fishing to complete ecological collapse and, eventually, the death of the wetland. To avoid that fate, watershed management and agriculture must draw less water, contribute less sediment, and add fewer pollutants than they have in recent decades, the authors write. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2023JD039538, 2024) **—Rebecca Dzombak,** *Science Writer*

New research suggests that the Anzali wetland, the "ecological gem" of Iran, could dry up by 2060. Credit: Hamid Hajihusseini via Wikimedia Commons, CC BY 3.0 (bit.ly/ccby3-0)

Our Breathing Earth: A Review of Soil Respiration Science

Earth scientist Stephanie Pennington measures soil respiration at the Smithsonian Environmental Research Center near Edgewater, Md. Credit: Ben Bond-Lamberty

The ground beneath our feet is exhaling. Steadily and without pause, through a process called soil respiration, plant roots and microbes release carbon dioxide (CO_2) into the atmosphere.

The amount of CO_2 that passes from the soil to the air is significant—almost an order of magnitude greater than human emissions. Computing this flow for the whole planet, and understanding how it may be changing, is complicated and uncertain because of gaps in observational data. Yet the calculation is essential for understanding the global carbon cycle and climate change feedbacks.

In a new review paper, *Bond-Lamberty et al.* summarize the past 2 decades of progress in soil respiration science. In one cited study, researchers girdled trees, or removed their outer layers, to mimic the effects of insects and tracked how tree stress influenced respiration. In another, researchers evaluated how respiration responds to soil wetted by rainfall. The synopsis recounts laboratory approaches and findings, explores the refinement of measurement strategies in natural settings, and chronicles methods for simulating and documenting soil respiration.

The authors emphasize how taking advantage of advances in areas such as machine learning and mechanistic modeling must proceed alongside efforts to diversify the global research community. Improving representation from lower-income regions will have the added benefit of bolstering data coverage and improving global soil respiration estimates muddied by uncertainty. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2023JG007637, 2024) **—Aaron Sidder,** *Science Writer*

The Escalating Impact of Global Warming on Atmospheric Rivers

Ribbons of water vapor called atmospheric rivers wind through the troposphere, moving the planet's moisture from near the equator toward the poles. These aerial waterways are responsible for about 20%–30% of the annual rain and snow in parts of Europe and the United States and more than 40% of precipitation in East Asia during that area's warm season.

Climate change is predicted to alter the timing and distribution of atmospheric rivers, potentially redistributing the global supply of water.

Zhang et al. used a suite of climate models called Coupled Model Intercomparison Project Phase 6 (CMIP6) to examine how the prevalence of atmospheric rivers has already changed and will continue to do so in a warming world from 1980 to 2099.

Rising surface temperatures will continue to increase moisture content in the air, leading to more frequent atmospheric rivers overall, the researchers found. Globally, these events will increase in frequency by 84% between December and February and by 113% between June and August under continued heavy fossil fuel use. Under medium greenhouse gas emissions, they will increase by 34% and 46% during the same time periods.

The northern Indian Ocean will see the most substantial increase, with atmospheric rivers doubling or perhaps even tripling in frequency. Greenland will also see a pronounced rise, with the interval between atmospheric rivers shrinking from an average of 59 days to 30–41 days, depending on how fossil fuel consumption progresses.

For regions unaccustomed to receiving heavy precipitation, these shifts could be disruptive. Sudden increases in precipitation can overwhelm infrastructure, leading to damaging flooding. The researchers write that the potential impacts "should not be underestimated." (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2023JD039359, 2024) **—Saima May Sidik,** *Science Writer*

Supercomputer Modeling Says, Step Aside Internal Tides

Waves don't take place just on the ocean's surface. Beneath the crests and troughs that we can see from above are internal tides, which form when tidal flows collide with seamounts, continental slopes, and ridges on the seafloor.

Internal tides play a significant role in ocean movements, influencing wave patterns and mixing of different ocean layers, for example, which in turn affect heat and carbon transfer and storage. Though internal tides are generally strongest below the surface, their effects on sea surface height are large enough to be detected by satellite altimeters. When scientists want to measure slower moving ocean features, such as eddies and currents, they isolate them by analyzing satellite altimeter data and removing the signals of internal tides.

Yadidya et al. used new supercomputer-driven modeling to forecast the global movement of internal tides. Their models accurately removed internal tide signals from sea surface height measurements without requiring empirical analysis. The modeling also provided hourly readings of sea surface height in 30- to 120-day analysis windows, offering insights into ocean movement that are missed by satellite measurements taken every 9–35 days.

These models provide many possibilities for future study of tidal activity, the researchers say, as well as information about all the layers of the ocean. The models' development could also drive a shift from making data-driven predictions about internal tides to using more dynamic modeling techniques.

Internal ocean waves are generated when tides beneath the surface pass over seamounts, continental slopes, ridges, or other rough seafloor surfaces. The surface expression of such waves can be seen here in Indonesia's Lombok Strait because of the water's reflection of sunlight. Credit: Jeff Schmaltz, MODIS Land Rapid Response Team, NASA GSFC

(*Geophysical Research Letters*, https://doi.org/10.1029/2023GL107232, 2024) **—Rebecca Owen,** *Science Writer*

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ARCTIC ICE PROJECT

TECHNICAL DIRECTOR AT ARCTIC ICE PROJECT: PART-TIME OR FULL-TIME

OVERVIEW:
Arctic Ice Project (AIP) is a nonprofit organization dedicated to slowing global warming and stabilizing the global climate by safely preserving and restoring Arctic sea ice through research, development and deployment of innovative solutions.

This **Technical Director (TD)** position is for a highly skilled PhD earth, climate science, or related field, preferably with cryosphere research experience. The ideal candidate would be a mid- to late-career established scientist/engineer with a strong professional network. Seeking an individual interested in either full or part-time, with experience working outside their institution (e.g., working with professional organizations, nonprofits, start-ups, etc.). TD reports to the AIP CEO.

PRIMARY AREAS OF RESPONSIBILITY:
- To shape, influence and steer, along with AIP leadership team, AIP's science and technology programs.
- To evaluate and ensure the effectiveness of AIP technologies through research and modeling approaches, materials testing, safety, performance testing and methods for deployment.
- To leverage internal/external resources and to provide expert feedback on our work through collaboration with top international scientists, research organizations, and technical publications.
- To manage and coordinate sponsored research partnerships with credible global institutions.
- To openly share findings through peer-reviewed scientific articles and presenting AIP work in key Arctic and climate-oriented journals and conferences.
- To prioritize, formulate and initiate new research projects, spawned by the results of ongoing projects.
- To collaborate with Indigenous Arctic communities, nations and multinational organizations to plan and implement ice restoration solutions.
- To identify partnerships and strategic alliances that add value and leverage resources available to support the mission and community.

EXPERIENCE/REQUIREMENTS:
- Strategic thinking and experienced science management with proven success in proposal development to secure external support to meet research costs of technology plans.
- Overseeing science and technology budgets and ensuring resource investments align vision with the technological needs.
- Providing leadership, guidance and oversight to technical teams including grants and technical contracts.
- Working collaboratively with diverse stakeholders and engaging in strategic partnerships.
- Tracking and managing all technical projects with respect to timelines, milestones and budget parameters.
- Demonstrating skill in communicating scientific concepts to non-scientific audiences
- Possessing interpersonal skills to enhance teamwork and interaction with staff, board members and external partners and volunteers.

MINIMUM QUALIFICATIONS:
- PhD in earth, climate or preferably cryospheric sciences and research

TO APPLY: https://findajob.agu.org/job/8023627/technical-director-at-arctic-ice-project-part-time-or-full-time/

OCEAN NETWORKS CANADA

DIRECTOR OF SCIENCE

DESCRIPTION
Ocean Networks Canada (ONC) invites applications for the position of **Director of Science**. As a pioneering organization that supports ocean discovery and innovation, ONC offers a stimulative, supportive environment within a multi-disciplinary culture, celebrating individuals and teams for their distinct cultural and knowledge backgrounds and innovative thinking.

THE POSITION
ONC is seeking a passionate and experienced leader and ocean science expert to drive the development and delivery of ONC's Science division. Responsible for ONC's scientific direction and national and international partnerships, the Director steers ONC in the scientific excellence and innovative thinking necessary to maintain ONC's leadership at the forefront of ocean observing.

Reporting to the President & CEO of ONC and as a member of the Executive team, the Director of Science provides strategic, executive, and operational leadership and oversight to the science division. The Science Director provides leadership and direction to a team of staff scientists who bring expertise across many scientific disciplines and serve as the essential interface between the global community of scientific researchers and the ONC observatory infrastructure capabilities. The staff scientists contribute to and support the publication of research results; collaborate directly with internal and external scientists and stakeholders to define data requirements for research projects; advise on uses and data interpretation; plan future initiatives; coordinate workshops; build collaborations; and support research teams in preparing experiments, including but not limited to funding proposals.

APPLICATION
To review additional information for this position and to apply - Please visit **https://findajob.agu.org/job/8023617/director-science/** Applicants must submit: a cover letter that summarizes their leadership experience, vision, and commitment to diversity; a curriculum vitae; and contact information for at least three references. Reference letters will only be requested from top applicants. Review of applications will begin in **April 2024**, and continue until the position is filled, ideally by **1 September 2024** (negotiable).

REQUIREMENTS
A visionary leader with a proven record of program development and management, the Director of Science has a Ph.D. in any discipline related to oceanography, marine science, or ocean technology, plus years of relevant experience consistent with a leadership role in either academia, industry, or government.

EDUCATION AND EXPERIENCE
- Doctoral degree in a relevant field of study
- 10 years of scientific leadership and/or senior-level research experience in a science program of national and international standing
- 10 years of supervisory experience
- Experience in developing, managing and directing research programs
- Experience in writing scientific proposals
- A record of publishing in academic journals

Dear *Eos*:

Earth's estuaries are hot spots of carbon cycling. Muskegon Lake is a highly productive urbanized estuary that drains the second-largest watershed in Michigan into the second-largest Laurentian Great Lake: Lake Michigan.

Our aim is to quantify the carbon flux in this dynamic ecosystem through experiments and time series measurements that track changes in oxygen concentration (as a metabolic proxy for equimolar changes in carbon) in the lake.

Here, graduate student Kaylynne Dennis collects surface water to fill clear bottles that will be deployed in Muskegon Lake to study daily rates of photosynthesis and dark bottles to study respiration. Biweekly experimental measurements will be complemented with seasonal shipboard and continuous time series measurements of oxygen concentration by the Muskegon Lake Observatory.

How will river loading, thermal stratification, wind mixing, and algal blooms affect in-lake carbon metabolism, and what effect will the ongoing El Niño conditions have on the net carbon balance of this estuary? Our results should shed light on these questions.

—Bopi Biddanda, Kaylynne Dennis, Tony Weinke, and **Eric Snyder,** Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich., and **Steve Ruberg,** NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Mich.

Send us your postcards at Eos.org

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