Eos

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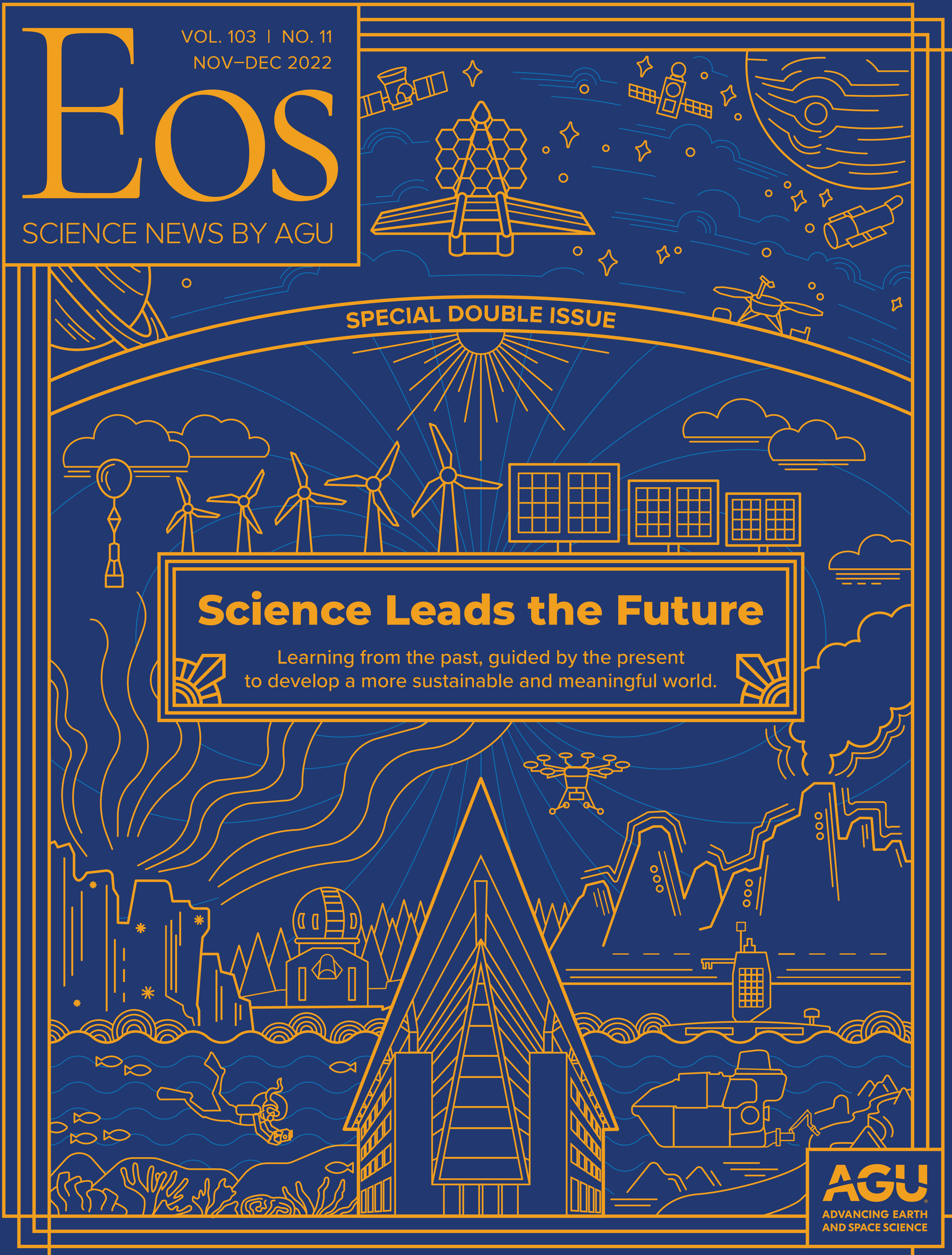
SPECIAL DOUBLE ISSUE

Science Leads the Future

Learning from the past, guided by the present to develop a more sustainable and meaningful world.



AGU
ADVANCING EARTH AND SPACE SCIENCE

Science Leads the Future, and the Future Is Now

As thousands of scientists bundle up for AGU's Fall Meeting 2022 in Chicago, we at *Eos* are reminded that "Science Leads the Future" and the future is science. This future, informed by the past and guided by the present, will be characterized by the contributions of individuals, communities, and coalitions with clear goals and practical benchmarks for achieving them.

The future of effectively monitoring permafrost in the Arctic has its roots in ice ages past, as illuminated by the unlikely friendship forged between an American scientist and Russian researcher in the 1990s. Learn more about Siberia, a mammoth named Willy, and post-Soviet friendships from Jenessa Duncombe in the latest edition of her series *The Curve* (p. 38).

The predicted impact of greenhouse gas emissions hasn't changed much in a century, John Aber and Scott V. Ollinger remind us (p. 58). They offer suggestions for clear, data-driven outlines to get the message across.

The Cold War fear of nuclear conflict has, unfortunately, resurfaced. On page 27, Alan Robock and Stewart C. Prager outline steps scientists can take to reduce the likelihood of such conflict. In the end, they believe, "the ultimate solution to the problem of nuclear weapons is to ban them globally."

At the onset of the COVID-19 pandemic, aerosol scientists were the sentinels warning of the airborne quality of the virus. The way policymakers and the public responded to these researchers framed the world we live in today, and the one we are building for the future. Richard J. Sima's "Indoor Air Pollution in the Time of Coronavirus" (p. 44) is a study in science, frustration, and, ultimately, hope.

An early diagnosis is also the hope of Matthieu Chartier's "The Alarming Rise of Predatory Conferences" (p. 64). Chartier offers suggestions to help the community secure a more trusted, transparent future.

Grassroots organizations are acting today to redefine university boards in the future. On page 52, Kimberly M. S. Cartier describes the efforts of Harvard Forward, Penn State Forward, and Yale Forward as these alumni groups organized to elect members to the powerful boards that decide how universities respond to climate change.

"Are We Entering the Golden Age of Climate Modeling?" (p. 30) asks Mark Betancourt in his analysis of exascale computing and the European Union's Destination Earth project. Exascale supercomputers, capable of a quintillion (10^{18}) operations per second, may revolutionize (resolution-ize?) the way scientists model and twin a diverse array of systems that contribute to Earth's climate. The new models may also help communities develop adaptation and mitigation strategies.

Finally, a group of scientists encourages their peers to give "Credit Where Credit Is Due" (p. 20) in an opinion from Mark A. Parsons, Daniel S. Katz, Madison Langseth, Hampapuram Ramapriyan, and Sarah Ramdeen. The traditional protocols surrounding academic citation and credit are outdated, they argue, and what is needed instead is a "wider designation of credit *everywhere* it is due."

From Arctic fungi to academic footnotes, change can be a slow process, but our community can implement some steps immediately. Science leads the future, and the future is now.

Caryl-Sue Micalizio, Editor in Chief

Eos

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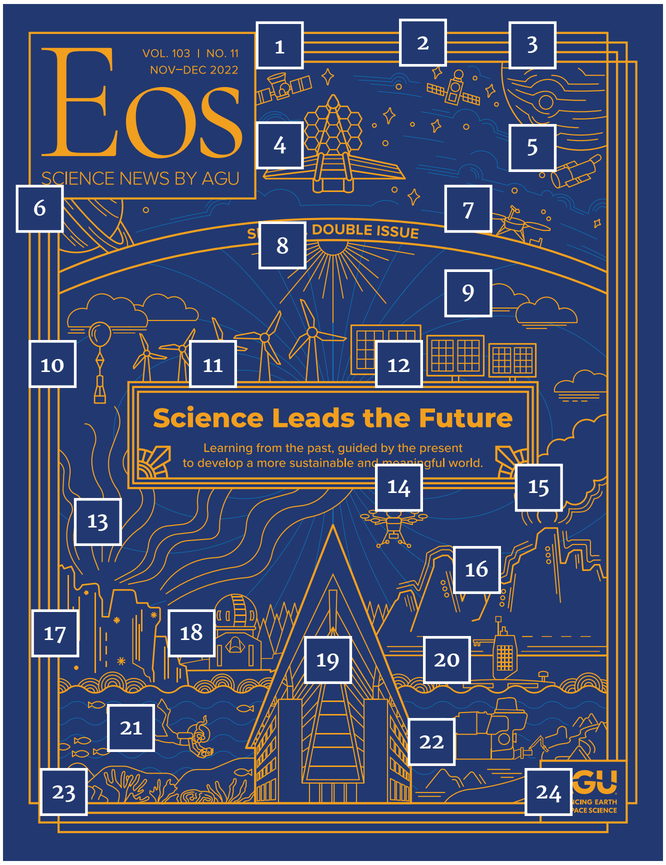
Randy Fiser, Executive Director/CEO



On the Cover

Design by Mary Heinrichs. Illustration elements are inspired by various *Eos* articles and AGU's scientific disciplines, as follows: (1) Transiting Exoplanet Survey Satellite (TESS) (bit.ly/Eos-shake-rattle-probe); (2) Jason-2/Ocean Surface Topography Mission (OSTM) (bit.ly/Eos-geodeticinfrastructure); (3) Jupiter (bit.ly/Eos-Jupiter); (4) James Webb Space Telescope (JWST) (bit.ly/Eos-JWST-images); (5) Hubble Space Telescope (bit.ly/Eos-Hubble); (6) Saturn (bit.ly/Eos-Saturn); (7) InSight (bit.ly/Eos-Insight); (8) the Sun (bit.ly/Eos-solar-encounter); (9) clouds (bit.ly/Eos-clouds); (10) weather balloons (bit.ly/Eos-Greenland-ice-sheet); (11) wind turbines (bit.ly/Eos-wind-farms); (12) solar panels (bit.ly/solar-perovskites); (13) aurorae (bit.ly/Eos-aurorae); (14) drones (bit.ly/Eos-drones); (15) volcanoes (bit.ly/Eosvolcanoes); (16) mountains (bit.ly/Eos-mountains); (17) glaciers and ice sheets (bit.ly/Eos-glaciers-ice-sheets); (18) telescopes and observatories (bit.ly/Eos-telescopes); (19) AGU (bit.ly/Eos-AGU-clean-energy); (20) saildrones (bit.ly/Eos-inside-a-hurricane); (21) scuba divers (bit.ly/Eos-seaclues); (22) HOV Alvin (bit.ly/Eos-Alvin-anniversary); (23) coral reefs (bit.ly/Eos-threatened-corals); (24) submarine channels (bit.ly/Eos-river-beneath-sea)

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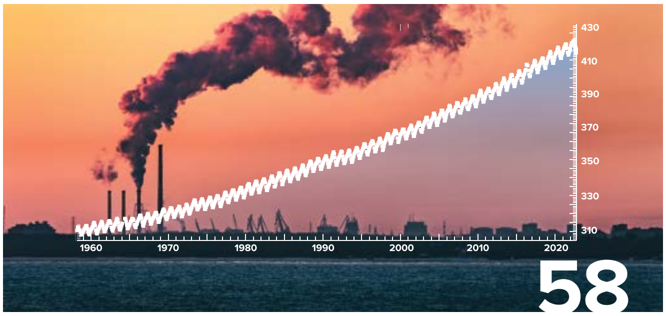
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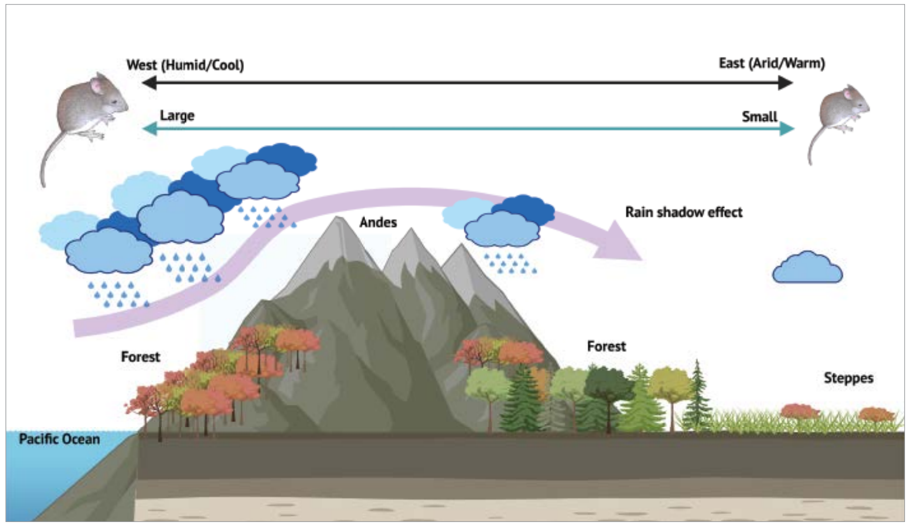
Rain Makes Skulls Bigger—in Mice

Mice that live on the colder, rainier western slopes of the Andes mountain range have larger skulls than the same species of mice that live in the warmer, drier eastern steppes and grasslands. Researchers have attributed these morphological differences to the rain shadow effect, a weather phenomenon common in coastal mountain ranges around the world that causes rain to preferentially fall on one side of the mountains.

"In this particular study, [longitude] mirrors the rain shadow effect from the Pacific Ocean over the Andes to the Patagonian grasslands on the other side," said lead researcher Noé de la Sancha, a mammologist at DePaul University and the Field Museum of Natural History in Chicago.



The western side of the Andes receives more rainfall than the eastern side as humid air from the Pacific Ocean rises and cools. The eastern side of the mountain range is in the rain shadow. The eastern dryness and aridity lead to fewer resources for animals like A. hirta, *which become consistently smaller than their western counterparts. Credit: Teta et al., 2022, https://doi.org/10.1111/jbi.14468*

In the Shadow of the Mountains

Environmental factors like temperature, precipitation, and elevation can influence the size and shape of mammalian species by controlling the availability of resources, namely, water and food. Generally speaking, de la Sancha explained, larger individuals within a species tend to live in environments that are at higher latitude, are at higher elevation, are colder, or receive more precipitation.

The researchers wanted to understand how the Andes, a mountain range that spans a long swath of western South America and contains a wide variety of ecosystems, might influence the morphology of the mammalian species that live there. "Nonflying small mammals, mainly represented by rodents… tend to be sensitive to ecological gradients, they tend to be abundant and diverse, [and] most have limited dispersal and thus live where they are captured," de la Sancha said. *Abrothrix hirta*, a shaggy, soft-haired mouse, "is an excellent species for this type of study because it is widely distributed in a region that includes both sides of the Andes," he said.

The team measured the sizes and shapes of 450 *A. hirta* skulls collected locally and also archived in museums. The mice represent 67 locations that span 19° latitude in southern South America and from the Pacific to Atlantic coasts in Patagonia and Tierra del Fuego. There were roughly even numbers of male and female specimens and specimens from west and east of the Andes. The researchers used 19 temperature- and precipitation-based metrics from a global climate database to quantify the mice's environmental conditions and looked for any trends between the size and shape of the skulls and the environments in which the mice lived. Some of the mice skulls were significantly larger than others, but the researchers struggled to explain why.

"While teaching the principle of the rain shadow effect during ecology class one day, it occurred to me it correlated very nicely with our results."

"None of the precipitation or temperature variables we tested best explained the size and shape of *Abrothrix hirta*," de la Sancha said. "Originally, our analysis recovered longitude as a very important variable to explain size and shape. And while teaching the principle of the rain shadow effect during ecology class one day, it occurred to me it correlated very nicely with our results."

The rain shadow effect describes how coastal mountain ranges shape regional airflow and precipitation. In the Andes, warm, humid air flows eastward from the Pacific Ocean. The mountains push the air upward, where it cools, condenses, and rains out on the western slopes. The now dry air continues to move eastward past the mountain peaks and descends over the steppes and grasslands, which then receive less precipitation than the western Andean forests.

In their data, longitude is a rough proxy for the Andean rain shadow effect, de la Sancha explained. Water and vegetation on the western slopes of the Andes are more abundant than in the east. The researchers suspect that the rain shadow cast over the eastern grasslands, which makes Patagonia warm and dry, provides fewer resources and helps keep eastern *A. hirta* smaller than their counterparts that live in the cooler, wetter, more resource-rich western Andean forests. The researchers published these results in the *Journal of Biogeography* (bit.ly/rain-shadow-effect).

A Changing Mountain Clime

Mountains cover about a quarter of Earth's land area, and most create some degree of

Specimens of the shaggy, soft-haired mouse Abrothrix hirta *show differences in size based on which side of the Andes Mountains they live. Credit: Pablo Teta*

rain shadow effect. This study "adds to a growing literature that uses mountain systems for understanding the effects of climate and vegetation change on species evolution and adaptation," said Anderson Feijó, a bioecologist at Beijing's Institute of Zoology at the Chinese Academy of Sciences. "The rain shadow effect is one of several examples of how mountains shape the environment of a region and ultimately affect the animals and plants living there." Feijó was not involved with this research.

As with all environments, climate change will likely have significant impacts on the ecologies of mountain regions and thus on the evolution of mountain species. Some climate models predict that the western Andean slopes will become wetter at higher elevations, resulting in larger mice farther up the mountains, de la Sancha said, whereas the Patagonian grasslands will become warmer and more arid, resulting in even smaller eastern mice. Mice that adapted to the ecologies of their side of the mountain might soon find that their environments no longer meet their needs.

"Their finding...reveals the strong connection between animals and their habitats, even across a short scale," Feijó said. "Consequently, one may expect that environmental changes, such as those linked to global warming, might reduce the fitness of animals in their own natural habitats."

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

Impact Crater off the African Coast May Be Linked to Chicxulub

In the world of impact craters, Chicxulub is a celebrity: The 180-kilometer-diameter maw in the Gulf of Mexico was created by a cataclysmic asteroid impact at the end of the Cretaceous that spelled the demise of most dinosaurs. Now researchers have now uncovered another crater off the coast of Guinea that might well be Chicxulub's cousin.

The newly discovered feature is also about 66 million years old. That's a curious coincidence, and it has scientists wondering whether the two impact structures might be linked. Perhaps Chicxulub and the newly discovered feature—dubbed Nadir crater—formed from the breakup of a parent asteroid or as part of an impact cluster, the team suggests in a new study in *Science Advances* (bit.ly/impact-structures).

Rocks of Concern

Every day, tons of cosmic dust rain down on our planet. That microscopic debris poses no danger to life on Earth, but its larger brethren are very much cause for concern: A space rock measuring hundreds of meters in size is apt to cause regional destruction, and the arrival of something measuring kilometers in size could spell global havoc.

That's what happened 66 million years ago when a roughly 12-kilometer-wide asteroid slammed into a shallow reef in the Gulf of Mexico. That event, now known as Chicxulub after the small town that's grown up nearby in Mexico, launched shock waves, powerful tsunamis, and blasts of superheated air that decimated life in the vicinity. Airborne particles—bits of dust, soot, and sulfate aerosols born from the sulfur-rich rocks that existed at the Chicxulub impact site—choked the atmosphere and plunged the entire planet into a sunlight-starved "impact winter" that lasted for years. When the air finally cleared, more than 75% of all species had gone extinct.

The newly discovered Nadir crater appears to have formed around the same time as that cataclysm. Uisdean Nicholson, a sedimentary geologist at Heriot-Watt University in Edinburgh, Scotland, and his colleagues discovered the candidate crater while they were poring over observations of seafloor sediments originally collected for oil and gas exploration. The team spotted the roughly 8-kilometer-wide structure in seismic reflection imaging data obtained off the coast of West Africa. "It was pure serendipity," said Nicholson.

Signs of an Impact

The putative crater is buried under roughly 300 meters of sediments topped by 900 meters of water, and its appearance strongly suggests it was created by a hypervelocity impact, said Nicholson. For starters, it's circular in shape, with a pronounced rim. Second, it contains a small central peak, a feature that often arises in large impact craters. And perhaps most important, there's clear evidence of deformed sediments—caused by faulting and folding—persisting hundreds of meters below what would be the crater's floor. "There are a lot of things that suggest it's an impact," said Gavin Kenny, a geochemist at the Swedish Museum of Natural History in Stockholm who was not involved in the research.

"It was pure serendipity."

Numerical simulations run by team member Veronica Bray, a planetary scientist at the University of Arizona, have suggested that the impactor was about 400 meters in diameter. The arrival of such an object moving at roughly 20 kilometers per second would have produced tsunami waves more than a kilometer high and ground shaking equivalent to that of a magnitude 7 earthquake, Bray estimated. But the mayhem that ensued, intense as it was, was mostly limited to a regional scale, said Bray. "This wasn't a global killer."

On the basis of assemblages of microfossils unearthed close to Nadir crater, Nicholson and his colleagues estimated that this feature formed at or near the end of the Cretaceous period. But it's too simplistic to assume that a pair of gravitationally bound asteroids—a binary asteroid—formed Chicxulub and Nadir crater in a one-two punch, the authors suggested. That's because of the extreme distance between the two sites 66 million years ago: roughly 5,500 kilometers. (They're even farther apart now—about

Scientists hope to drill into a newly discovered impact crater off the west coast of Africa to explore whether and how it's linked to the famous Chicxulub impact 66 million years ago. Credit: iStock.com/guvendemir

8,000 kilometers—because of spreading of the Atlantic seafloor.) Binary asteroids tend to hit much closer to one another: The one example on Earth of a so-called "impact doublet" formed by a binary asteroid is characterized by craters just a little over 10 kilometers apart. "So Chicxulub and Nadir couldn't have formed from a direct hit of a binary asteroid," said Nicholson.

"There are a lot of things that suggest it's an impact."

Looking to Jupiter

A more likely scenario, Nicholson and his collaborators suggested, is something akin to what happened to comet Shoemaker-Levy 9. In 1992, the roughly 2-kilometer-diameter comet fragmented into more than 20 pieces after passing very close to Jupiter. Two years later, those fragments slammed into the gas giant over the course of several days, creating a series of dark scars that stretched across a wide swath of the planet.

Perhaps a similar breakup of a common parent asteroid occurred near Earth 66 million years ago, Nicholson and his colleagues proposed. An asteroid—there's good evidence that the Chicxulub impact was due to an asteroid rather than a comet—orbiting Earth could have been torn apart by our planet's gravity. Those fragments could have then dispersed sufficiently in space to smash into Earth within days of each other yet in widely separated locations, the researchers suggested.

Another possibility is that one or more asteroids collided somewhere in deep space—most likely in the asteroid belt between Mars and Jupiter—and an ensemble of cosmic shrapnel traveled en masse to Earth. The result would have been an uptick in cratering that persisted not over days, as in the case of the breakup of a common parent asteroid, but over a million or so years. Scientists are aware of only one such event—known as an impact cluster—in Earth's history, and it occurred roughly 460 million years ago. "We think an asteroid parent body broke up somewhere in the solar system and sent material flying toward Earth," said Kenny.

The impact cluster scenario might be more likely, Nicholson and his colleagues suggested, because a third large crater—the 24-kilometer-diameter Boltysh crater in central Ukraine—also dates to around 66 million years ago. Research published last year suggested that Boltysh formed just 650,000 years after the Chicxulub impact (bit.ly/Boltysh-crater).

There's also the possibility that Nadir crater was simply created by an unrelated impact, Nicholson and his colleagues acknowledged. Perhaps a stroke of bad cosmic luck led to Earth being pummeled twice in relatively close succession.

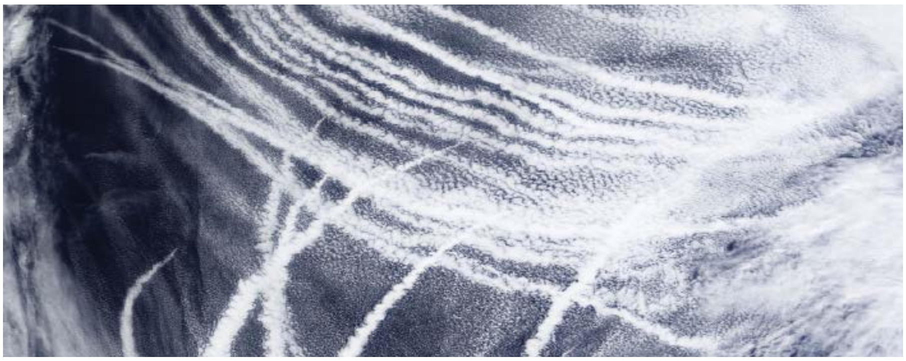
Going Deep

It's clearly key to more precisely constrain the age of Nadir crater, Nicholson and his collaborators maintain. Right now, the uncertainty in the structure's age is about a million years, too large to discriminate between the breakup of a common parent asteroid and impact cluster scenarios.

Drilling sediment cores from the crater would allow scientists to look for stratigraphic signatures like the iridium layer from Chicxulub that could yield a much more precise date. Nicholson and his colleagues recently submitted a drilling proposal to the International Ocean Discovery Program to do just that.

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

Tracking Climate Through Ship Exhaust



Scientists are taking a closer look at emissions associated with ship tracks, like these crossing the Pacific Ocean south of Alaska. Credit: NASA

A total of 99,800 commercial ships sail the seas, carrying around 90% of the world's trade in goods. Their operation is vital—the transport of COVID-19 vaccines, for instance, wouldn't have been possible without them.

The fuel oil that runs these immense vessels can contain up to 3,500 times more sulfur than diesel used for land vehicles. When the fuel is burned, large amounts of sulfur oxides and other aerosols are released into the atmosphere. These aerosols increase the concentration of droplets in marine low clouds, which makes the clouds appear brighter. These bright clouds trail ships and can be seen in satellite images.

In 2018, Tianle Yuan, a University of Maryland, Baltimore County atmospheric scientist at NASA's Goddard Space Flight Center, and his team began developing a machine learning algorithm that automatically identifies these "ship tracks." After years of refining the algorithm with satellite imagery, they created the first global map of ship tracks with data spanning the past 18 years.

"Before our study, the largest samples contained about 5,000 ship tracks, and that's already a huge effort," Yuan said. "But now we have hundreds of thousands, maybe millions."

The team's first finding after analyzing the monitoring map is good news for both people and ocean health.

Regulations Are Working

Sulfur oxides are harmful to people's respiratory health and damaging to ocean ecosystems. When the particles reach the atmosphere, they quickly become surrounded by water and promote cloud creation. Those clouds produce acid rain, which affects crops and forests near the coasts, and contribute to ocean acidification, which likely reduces marine ecosystem services.

As a response to shipping-related air pollution, the United Nations' International Maritime Organization (IMO) started implementing limits on the sulfur content in fuels. In 2015, a sulfur content limit of 0.1% was established for ships sailing within Emission Control Areas (ECAs). Outside ECAs, the sulfur content limit was reduced in 2020 from 3.5% to 0.5% . Together, the latest regulations account for an annual reduction of 8.5 million metric tons of sulfur oxides—77% of total emissions, according to IMO agency data.

"Most of the ship tracks just disappeared. Regulations are working."

The results obtained by Yuan and his team, published in *Science Advances* (bit.ly/sulfur-regulations), put those numbers into perspective. "Within the ECAs, most of the ship tracks just disappeared," Yuan said. "Regulations are working."

Although the COVID-19 pandemic affected maritime trade, the number of ship tracks in ECAs continued to decline even as trade began to recover between late 2020 and early 2021, Yuan said.

However, when analyzing data from the U.S. West Coast, the scientists noted that since the implementation of the ECA limits in 2015, several ships changed their routes to the south, outside the ECA. Shipping traffic from Los Angeles and San Diego ports decreased, and hot spots were found in Baja California, just beyond the ECA.

Although there is no hard evidence, Capt. Ricardo Valdés of Mexico's Secretariat of the Navy "would also not doubt" that ships may be evading ECAs to avoid buying cleaner fuels, which are more expensive. Valdés has been sailing for 35 years and is very familiar with shipping policies and practices.

In fact, in 2018, Mexico's Ministry of Environment and Natural Resources (SEMARNAT) sought to create its own ECA because the lack of regulation on emissions was causing vessels to use cheap, polluting fuel when arriving in Mexican national waters. "We want to control the emissions from the ships that transit our waters [75% of which are foreign], so that these emissions are as few as possible," said Rodolfo Lacy of SEMARNAT.

Ultimately, the IMO declined Mexico's initiative because the country is not a signatory to Annex VI of the International Convention for the Prevention of Pollution from Ships, the mechanism through which emissions limits are implemented.

Although the IMO already has an emissions inventory based on automatic identification system data that lets it identify ship emissions, fuel consumption, and energy use, Yuan's team's algorithm "is useful for validating some of the bottom modeling that's used as the basis for IMO decisionmaking," said environmental scientist Bryan Comer, who leads the International Council on Clean Transportation's marine program.

The algorithm could also be "an excellent tool" for monitoring evading ships and their emissions, Valdés said, but it will be useful only if Mexico works to adhere to IMO agreements. "[Mexico] can't require a foreign ship to comply with some standards if its own ships don't.... The tools and legislation exist, but political will is needed."

The Road to Decarbonization

In addition to emitting sulfur aerosols, bright ship tracks reflect the Sun's rays, a process that generates a cooling effect in the atmosphere. However, measuring this effect is extremely difficult because environmental conditions in each region affect clouds in different ways.

"The tools and legislation exist, but political will is needed."

The Intergovernmental Panel on Climate Change (IPCC) has stated that aerosol-cloud interactions constitute the biggest uncertainty in climate projections. Recent studies have shown that although global air pollution has decreased by up to 30% from 2000 levels, cleaner air may have increased warming by 15%–50% (bit.ly/aerosol-effective-climate-forcing). Still, the IPCC report points out that "strong, rapid and sustained reductions in methane [and other greenhouse gas] emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."

The IMO is aware of this. Comer explained that decarbonizing the maritime sector would produce benefits to both health and climate. The main issue, he said, is that decarbonization will reduce the atmospheric concentration of greenhouse gases. "We should not take any steps backward," he said.

For Columbia University climate scientist James Hansen, Yuan's work is an important element that will help scientists better understand the complex role of aerosols in climate change. The constant change of clouds makes it extremely difficult to study how they interact with aerosols, Hansen said. But ship tracks are perfect laboratories to study these interactions. There is very little change inside and outside of the plume of exhaust emitted by ships as they sail under the clouds, so scientists can attribute changes in the clouds more directly (though never entirely) to the aerosols.

"The radiation balance of the planet seems to be affected as we expected, but the record needs to be longer to quantify the impact," Hansen said. "Humanity is in the process of doing a large-scale experiment with the planet that potentially can provide important information about future climate."

By **Humberto Basilio** (@HumbertoBasilio), Science Writer

Major Investment in Air-Conditioning Needed to Address Future Heat Waves

During Europe's mid-July heat wave—when temperatures topped 40°C—countries such as Spain and Germany recorded thousands of excess deaths as people succumbed to heat-related injuries and illnesses. Earlier in the year, India and Pakistan experienced their hottest March on record, with an unusually early heat wave that killed at least 90 people.

By the 2050s, large swaths of the world will need some form of air-conditioning (AC) to ride out these extreme heat waves or face deadly consequences, according to new research published in *Energy and Buildings* (bit.ly/extreme-heat-waves). But few countries have anywhere near enough cooling capacity to protect residents.

Heating Beyond Human Limits

With our unique ability to sweat off excess heat, humans have adapted to life in a wide range of climates. But there is a limit to what we can tolerate before our internal cooling system can no longer operate. Evaporative cooling of sweaty skin is particularly inefficient when the surrounding air is already heavy with humidity.

When the mercury spikes, people around the world turn to shade, swimming, and fans to keep cool. Relatively few rely on air-conditioning. In the hottest regions of the world, including Indonesia and India, only about 8% of homes currently have an AC unit. In Europe, that number tops out at 20%.

With more frequent heat waves on the horizon due to climate change, mechanical cooling may become a necessity, however. "Severe heat has acute impacts, and air-conditioning is an extremely effective way to protect against those impacts," said Noah Diffenbaugh, a climate scientist at Stanford University who was not involved in the study.

An Air-Conditioned Future

To assess how actual heat stress and risks will change, scientists turned to the perceived temperature, called the wet-bulb temperature, which conveys how hot it feels considering humidity, temperature, Sun angle, wind, and cloud cover. On days when the wet-bulb temperature exceeds the threshold above which the human body cannot easily adapt, air-conditioning will be needed to limit excess deaths.

In the new study, the researchers used climate models to predict the number of days when that threshold would be passed in urban areas around the world under both a "business-as-usual" greenhouse gas emissions scenario and one in which emissions increase drastically by the 2050s. They then calculated the cumulative electricity demand from air conditioners in each country during these extreme heat events, assuming each unit was on for 6 hours a day.

The scientists had been researching how to decarbonize India when they realized they needed to understand how energy demand would increase because of climate change, said Peter Sherman, a climate scientist at Harvard University and lead author of the study.

Previous studies had projected demand from gross domestic product and population growth, he said, "but what's often not considered is increased demand for electricity associated with air-conditioning."

"What's often not considered is increased demand for electricity associated with air-conditioning."

Because climate models are global, the group decided to provide these estimates for countries around the world, Sherman said.

More than 80% of urban residents in most countries (including wealthier countries such as the United States and Japan, and developing countries such as India and Indonesia) will need air-conditioning to ride out extreme heat waves by the 2050s, according to the high-emissions scenario used by the researchers. In the United States and Japan, 90% of homes already have at least one air

Sławomir Kowalewski, Pixabay

conditioner, so installing additional units does not pose a major challenge. However, in Indonesia and India, only 8% of homes have units. In Indonesia, air-conditioning during days when the wet-bulb temperature exceeds the threshold could account for up to 75% of the country's current total electricity demand, according to the study.

"The largest source of uncertainty in the future climate is the human dimension."

Considering population growth, urbanization, and climate change over the next 30 years, some of the world's hottest places will need major investments in air-conditioning to meet demand during extreme heat events, according to the study. The tropics are particularly vulnerable because their high heat and humidity make for deadly wet-bulb temperatures, and some of these areas have the lowest current rates of AC use. These areas are also highly sensitive to the different emissions scenarios the study evaluated.

Residents of urban centers in the tropics, therefore, face a particularly tough cooling future, especially if the world does not curb greenhouse gas emissions.

"The largest source of uncertainty in the future climate is the human dimension," said Diffenbaugh.

Cooling Begets Warming

When calculating energy demand, the researchers assumed that increased air-conditioning usage will come in the form of ductless mini split units—wall-mounted air conditioners designed to cool a single room. However, these units have a high up-front cost, and in developing countries, cheaper, less efficient window units will likely fill the demand, said Shelie Miller, an environmental engineer at the University of Michigan who was not involved in the study. "If anything, [the study's researchers] may be underestimating the electricity demand because they are assuming a much more efficient unit than window ACs."

But blanketing the world even in high-efficiency air conditioners would strain electrical grids and generate greenhouse gases.

Air conditioner manufacturing and usage account for 4% of global greenhouse gas emissions—more than the aviation industry produces, said Jason Woods, a research engineer at the National Renewable Energy Laboratory who was not involved in the study.

"More air-conditioning means more carbon dioxide emissions, which then means more climate warming, which means more air-conditioning energy use," Woods said. To break that cycle, we need to develop more efficient cooling technologies and power those systems with renewable energy, he added.

Unequal Cooling

The findings highlight widely disparate access to cooling between wealthy and developing nations. Some studies have shown that the gap exists even within individual countries or cities.

"It's the more affluent people who have access to this cooling," said Neil Jennings, a geographer at Imperial College London who was not involved with the study. "The presence of that cooling then means that more heat [from the units] is being dumped out into the streets, which then means that those who don't have access to cooling are exposed to even higher temperatures."

Renewable energy sources, more efficient cooling solutions, and a return to traditional building practices—such as using dense building materials, windows, and shade to maximize insulation and airflow—may be needed to address the growing number of extreme heat days projected to hit some countries, Woods noted.

"I think [the study] really highlights the need to have action now," Miller said, "rather than as things continue to get worse over time."

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

Can These Rocks Help Rein In Climate Change?

The world's oceans play a key role in sucking up carbon from the atmosphere. Until anthropogenic carbon emissions began on a mass scale with the Industrial Revolution, ocean carbon uptake was one part of a land-ocean-atmosphere juggling act that kept the carbon cycle roughly in balance.

Now, a California-based company wants to use green sand to exploit the carbon sponge of the ocean to avoid the worst outcomes of global warming.

The Need for Speed

Vesta is a private company that believes it can speed up the ocean's long-term carbon sequestration process by treating coastal areas with crushed olivine. Although high-quality olivine can be used as a gemstone (peridot), it is a relatively inexpensive mineral whose ability to weather very quickly has long been studied as a means of enhanced weathering or ocean alkalinization, which some scientists have proposed as a way to mitigate climate change.

In the natural process of weathering, rocks are broken down by phenomena such as rain and extreme temperatures. Rain absorbs carbon dioxide (CO_2) from the atmosphere and forms bicarbonate ions when it reacts with rocks rich in silicate and magnesium, like olivine. The bicarbonate flows into the ocean, where it is ingested by marine organisms to create shells and exoskeletons; these shells as well as precipitates of the weathered minerals themselves can form limestone and other carbonates that store carbon for thousands of years. The bicarbonate also acts as a kind of antacid in the ocean, helping to fight ocean acidification.

In what Vesta describes as coastal carbon capture, the weathering process is accelerated by grinding large amounts of olivine into beach and seafloor sand, increasing the surface area of the mineral available for chemical reaction with seawater.

The idea isn't new, and the environmental side effects are ambiguous. The operation would expend energy and, potentially, carbon emissions. Vesta has also partnered with the largest dredging company in the United States, raising questions about the environmental impact on pelagic communities around the seafloor.

"While the idea of accelerating the Earth's natural geological carbon removal process was proposed in 1990 and various papers had

Olivine could increase the ocean's potential as a carbon sink, but adding it to beaches has significant environmental and economic caveats. Credit: James St. John/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

been published, there was no progress toward field trials," said Tom Green, CEO and cofounder of Vesta. "Various scientists have called for field trials, including in late 2021 the National Academies of Sciences, Engineering, and Medicine in their report on ocean carbon dioxide removal [CDR]" (bit.ly/CO2-removal).

Will It Scale?

Whether coastal carbon capture could put a sizable dent in the nearly 32 gigatons of CO_2 that society is pumping into the atmosphere annually remains unclear. Vesta said it is developing techniques that would remove at least a gigaton of atmospheric CO_2 per year.

In addition to environmental concerns, another key question is whether coastal carbon capture is financially practical.

"Our analysis indicates that on a large scale, coastal carbon capture could remove CO_2 for $35 per ton, which is cheaper than other permanent forms of CO_2 removal," said Green. "At the moment, it is much more expensive, since we are operating at small scales and optimizing for rigorous scientific study rather than cost."

There are also questions about the science. Earlier this year, a *Frontiers in Climate* study of olivine weathering in simulated seawater found that "CO_2 uptake is reduced by a factor of 5 due to secondary mineral formation and the buffering capacity of seawater (bit.ly/olivine-weathering). In comparable natural settings, olivine addition may thus be a less efficient CDR method than previously believed."

In a blog post responding to the paper, Vesta said the lab-based study had "limited applicability to field settings and it would not be prudent to draw significant conclusions about the feasibility of Coastal Carbon Capture from it." The company also said that studies like a 2017 paper in *Environmental Science and Technology* confirm the basic viability of its approach (bit.ly/olivine-dissolution).

"I like olivine as a CO_2 sink, but I think one has to grab the CO_2 from the air before the alkalinity reaches the ocean," said David Archer, a geophysics professor at the University of Chicago who is not involved with Vesta. Archer pointed to an *Environmental Research Letters* paper analyzing ocean alkalinization along the Great Barrier Reef (bit.ly/alkalinity-injection). "Everyone assumes that if you add base to the ocean, it will pull CO_2 from the atmosphere, but this will take thousands of years."

"We know that nature neutralizes carbon dioxide through a process based on the weathering of silicate rocks. It seems highly likely that humans could accelerate this process," said Ken Caldeira, a senior scientist emeritus at the Carnegie Institution for Science's Department of Global Ecology who has done experiments adding alkalinity to seawater; he is not involved with Vesta. His main question is not whether the approach would work but whether its economic and environmental costs are worthwhile given the massive scale needed to make an impact.

"Maybe mineral weathering and alkalinity addition to the ocean can play a useful role. But we won't know if it can play a useful role unless we try," said Caldeira. "We should expect some bumps in the road. But the biggest barrier is likely to be the massive scale of our carbon dioxide emissions."

With millions of dollars from crowdfunding, grants, and corporate investments, Vesta is pushing ahead with field tests. It recently launched a pilot project in New York and has plans for further trials in the Dominican Republic as well as elsewhere in the United States.

By **Tim Hornyak** (@robotopia), Science Writer

A New Approach to an Unresolved Mystery in Climate Economics

An open question in economics is whether shifts in temperature have long-lasting, permanent impacts on economic productivity. An economic slowdown after an unusual event, like a heat wave, might be troubling but temporary. Economic growth deflating over a long period, however, is much more problematic.

Understanding this question is essential for calculating the social cost of carbon, a critical metric for governments weighing future infrastructure and policy decisions.

Now, researchers from the United States and Italy have found evidence of changes to economic growth associated with temperature shifts. These changes occurred in the gross domestic products (GDPs) of about a quarter of the world's countries over 10–15 years.

"The question here is whether an economy is able to come back from these shocks year to year, or whether the shocks permanently change the pathway of the country's economy," said climate economist and Ph.D. student Bernie Bastien-Olvera of the University of California, Davis, who led the study. His work revealed that temperature shifts led to persistent changes in economic growth, helping some countries while hurting others.

In Australia, for instance, the study found that a 0.1°C increase in temperature over a decade might cause a 1% decrease in annual GDP growth.

The study exploited a technique that's never been applied to this question before. Using innovative filtering, the researchers zeroed in on climate trends instead of hard-to-parse day-to-day weather shifts.

Stanford University climate economist Marshall Burke, who didn't participate in the work, said that standard economic analyses, which miss these long-term impacts, "could be dramatically underestimating the economic impacts of a warming climate."

The latest findings would likely increase the social cost of carbon.

Filtering for the Truth

Past research into the persistence of temperature change effects on the economy has been "mixed and heavily debated," said climate economist Franziska Piontek of the Potsdam Institute for Climate Impact Research in Germany, who wasn't involved in the research. Previous work relied on a classical economic technique comparing the lagged effects of temperature changes on economic metrics.

Instead, Bastien-Olvera and his colleagues filtered out short-term changes in temperature but kept more extended, slower developments and patterns. They focused on the temperature swings of naturally caused climate phenomena, like the El Niño–Southern Oscillation and the Pacific Decadal Oscillation, a cycle in the ocean and atmosphere that alters the temperature of Pacific waters.

They compared the temperature shifts with World Bank data on the GDPs of more than 200 countries spanning 6 decades.

The long-term temperature changes barely edged over 0.1°C, but the change correlated with impacts on GDP growth in 22% of the countries. Persistent and negative temperature impacts weren't more likely to happen in low- or high-income countries or warm or cool countries, the researchers found.

Bastien-Olvera and colleagues published the research in *Environmental Research Letters* (bit.ly/temperature-variability).

"This is a very clever paper," said climate finance researcher Riccardo Colacito of the University of North Carolina at Chapel Hill. "These results lend themselves to the interpretation that temperature shocks are more likely to have a growth rather than a level effect."

Carbon's Social Cost

The bread and butter models of climate science and economics—integrated assessment models—rely on economic assumptions about, among other things, GDP growth. Specifically, these models assume no persistent effects from temperature changes on GDP growth. The latest research has cast doubt on that assumption.

These models also estimate the social cost of carbon, defined as the total present and future damage caused by an additional ton of carbon dioxide released into the atmosphere. "It's one of those numbers that appear everywhere in climate policy studies," said Bastien-Olvera.

Raising the social cost of carbon upcharges fossil fuel activities that carry higher social costs than sustainable, renewable projects. The latest findings would likely increase the estimation of the social cost of carbon, said Bastien-Olvera.

The work "confirms the concern voiced by other scholars that rising temperatures are extremely detrimental to the future growth prospects of the global economy," said Colacito.

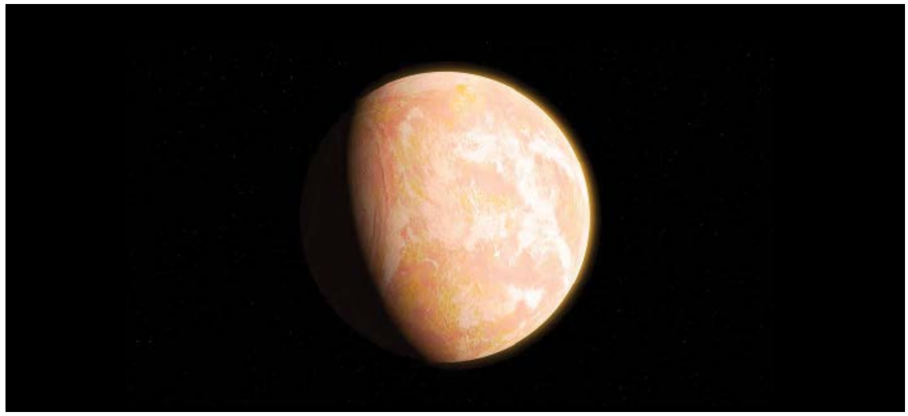
A new study focused on the temperature swings of naturally caused climate phenomena, like the El Niño–Southern Oscillation that brought this bloom to Chile's Atacama Desert, and their impact on local, regional, and national economies. Credit: Javier Rubilar/Flickr, CC BY-NC-SA 2.0 (bit.ly/ccbyncsa2-0)

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

Early Life Learned to Love Oxygen Long Before It Was Cool

Early life happily thrived in an oxygen-free world. These microbes, our earliest ancestors, subsisted on molecules such as hydrogen and lived in the hot inner recesses of Earth's shallow crust. At some point, however, life developed a tolerance for oxygen, and evidence suggests it happened well before the world's oceans and atmosphere were awash with the element.

New research has shown that a stew of broken rocks, churned in near-boiling water, may have seeded this transition. The finding, published in *Nature Communications*, explains how life may have developed the biologic tools to deal with, and ultimately thrive in, oxygen-rich environments (bit.ly/oxidant-production).



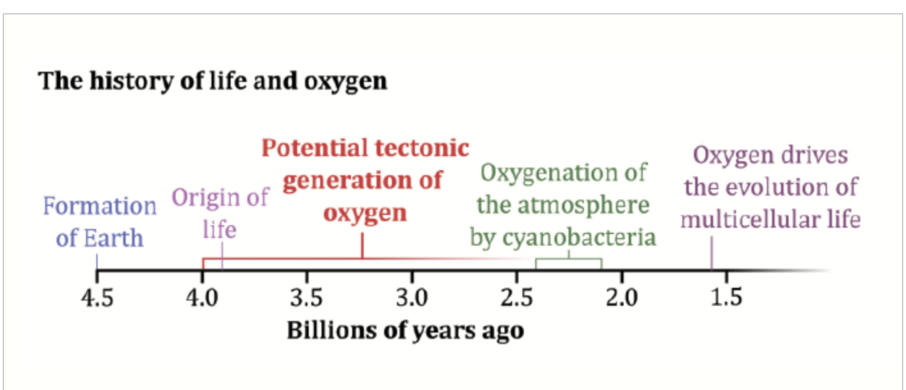
Early life evolved in a very different world. Credit: NASA Goddard Space Flight Center/Francis Reddy

> **"The role of free oxygen in life is a bit of a double-edged sword."**

Rocks on early Earth had plenty of oxygen. But it was locked in the solid crystal structures of minerals such as quartz and feldspar and so was mostly invisible to surrounding life. Only after the Great Oxidation Event around 2.4 billion years ago—when life learned how to photosynthesize—was "free" oxygen abundant in the oceans and atmosphere.

However, genetic reconstructions of 3.5-billion-year-old microbes suggest they possessed enzymes that could convert some of oxygen's more reactive and damaging forms (such as hydrogen peroxide) into usable oxygen (O_2) 1 billion years before the Great Oxidation Event.

Until now, scientists have struggled to explain why microbes had the tools when the gas was virtually missing from the biosphere. Researchers have been exploring the idea of a nonbiologic source of O_2 and reactive forms of oxygen to explain the mystery, said Tim Lyons, a biogeochemist at the University of California, Riverside and head of the Alternative Earths Astrobiology Team. Lyons was not involved in the new research.



Life developed a tolerance for oxygen long before the Great Oxidation Event 2.4 billion years ago. Credit: Jon Telling/Jordan Stone/Newcastle University

Freeing Oxygen

While experimenting with chemical reactions that occur at the base of glaciers, where free oxygen is scarce, the researchers stumbled onto a way to generate hydrogen peroxide, said Jordan Stone, a doctoral student of geochemistry at Imperial College London and lead author of the study.

As part of his master's project at Newcastle University, Stone filled thumb-sized glass tubes with either basalt or granite—analogues of oceanic and continental crust—that had been crushed under 100% nitrogen to simulate early Earth conditions. He then added water that had been stripped of free oxygen and heated the tubes. At temperatures above 80°C, hydrogen peroxide formed.

Similar conditions existed in Earth's crust at mid-ocean ridges or at depths greater than about 1 kilometer. There, hot, oxygen-free, water-hosting early forms of life percolated. Fracturing the surrounding rocks—say, during an earthquake, when two sides of a fault crunch past each other—releases chemicals from imperfections in the rocks, which then react with the water to make hydrogen peroxide, according to the researchers. This reactive form of oxygen can break down in the environment, or microbes can convert it to O_2, Stone said.

The process could have started when plate tectonics began, roughly 4 billion years ago, Stone said, giving microbes more than a billion years to adapt.

Early Life's Oxygen Problem

"The role of free oxygen in life is a bit of a double-edged sword," Lyons said.

Living in hot waters within Earth's crust, the microbes would have been exposed to this geologically formed hydrogen peroxide. But this and other reactive forms of oxygen, produced as intermediate products of chemical reactions, are damaging to life, Lyons said. They destroy DNA and other life-sustaining molecules.

"Early life had to figure out how to deal with this," Lyons said. "It was just an environmental hand that it was dealt." In response, the early microbes evolved antioxidant enzymes that converted damaging reactive oxygen to something that is not harmful.

"[This period] kind of works as a stepping stone," Stone said. As life evolved to protect itself from a low dose of hydrogen peroxide, it was developing the tools to thrive during the future onslaught of oxygen during the Great Oxidation Event.

"Later life developed this ability to take advantage of all the O_2, through aerobic respiration," Lyons said.

The work provides a realistic geologic explanation for early life's antioxidant enzymes, Lyons said. "It's a really nice study, and it addresses, I think, one of these really fundamental questions about life's ability to adapt to things."

"Maybe if we can find out how life originated on Earth, then we can find out how life originated on other planets as well."

An understanding of the complex interactions of life with its environment is helping scientists answer quandaries beyond our world. "Maybe if we can find out how life originated on Earth, then we can find out how life originated on other planets as well," Stone said.

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

U.K.-Based Geoscientists Trapped in European Funding Impasse

Both U.K. and international geoscientists working in the United Kingdom are caught in the middle of an argument between the U.K. government and the European Union (EU), threatening access to Europe's flagship funding program, Horizon Europe. Researchers may be faced with the choice of losing Horizon Europe funding or moving to an EU country.

Following Brexit, the United Kingdom was set to maintain close ties with Horizon Europe and with other EU science programs, including the Copernicus Earth observation framework and Space Surveillance and Tracking. But involvement is now threatened by a political disagreement over trading arrangements in Northern Ireland.

"It's a disaster for U.K. and EU science. No one wins from this misuse of science cooperation as a pawn in political disputes," said Jonathan Bamber, an Earth observation and cryosphere researcher at the University of Bristol who has a leading role in several current European research projects.

Horizon Europe

Horizon Europe has a budget of €95.5 billion (almost $100 billion) for the period 2021–2027. It is a vehicle for researchers to access funds and collaborate on global challenges such as climate change, energy, and food security. Funds and leadership opportunities are open to institutions within the 27 EU member states, as well as to those in Norway, Turkey, and 14 other associate countries.

Following the United Kingdom's departure from the EU on 1 January 2020, the United Kingdom was on track for Horizon Europe associate status as part of a broader agreement on trade and cooperation. But ratification of that deal has stalled because of issues surrounding Horizon Europe's Northern Ireland protocol—special measures designed to uphold EU trade rules while protecting the 1998 Good Friday Agreement that helps maintain peace in Northern Ireland.

The EU has yet to sign the deal and in June 2022 launched legal action against the United Kingdom, accusing it of failing to comply with the Northern Ireland protocol, mostly surrounding customs and excise fees. In response, the U.K. government launched formal consultations with the EU in August 2022, with former U.K. prime minister Liz Truss accusing the EU of "repeatedly seeking to politicise vital scientific cooperation."

As of mid-October 2022, debate… remains at an impasse. "The situation for U.K. science has never been so gloomy, and things will only get worse," said Andre Geim, a Nobel prize–winning physicist based at Manchester University, in an interview with the *Observer*.

"If the U.K. is not associated [with Horizon Europe], it makes taking a leadership role more risky, more uncertain, and subject to the vagaries of national decisions and politics."

Researchers in Limbo

In the thick of this political row, scientists in the United Kingdom face an uncertain future. Many are involved in current European research projects or are midway through the process of applying for Horizon Europe funding. Indeed, back in June the European Research Council (ERC)—one of the key bodies managing Horizon Europe grants—confirmed that 143 U.K.-based researchers would lose their ERC grants unless they relocated to an eligible institution within the EU.

Johannes Bahrke, a European Commission spokesperson, said the contested Trade and Cooperation Agreement provided no specific obligation for the EU to associate the United Kingdom with its programs or a precise deadline to do so. Bahrke confirmed, however, that researchers affiliated with U.K. institutions can still apply to Horizon Europe calls for proposals and undergo the evaluation procedures.

The issue is that grant agreements involving funding to U.K. entities cannot be signed until the United Kingdom has associate status. "Entities from nonassociated third countries are eligible to participate in Hori-

Disputes surrounding Brexit and European policies toward Northern Ireland threaten the status of researchers affiliated with U.K. institutions. Credit: iStock.com/Tanaonte

zon Europe projects without receiving [EU] funding," Bahrke said.

To reassure researchers at U.K. institutions, the U.K. government published its "Plan B," which addresses procedures in the event that the United Kingdom does not secure associate status. Plan B includes a commitment to fund all U.K. entities in Horizon Europe consortia for which grant agreements are signed before 31 March 2025. It also contains longer-term plans for U.K. participation in Horizon Europe projects via "Third Country" status and the creation of alternative funding mechanisms.

Bamber welcomed the government's interim support but feared that such a unilateral approach could never compete with full participation in Horizon Europe. "If the U.K. is not associated, it makes taking a leadership role more risky, more uncertain, and subject to the vagaries of national decisions and politics rather than being part of a legally binding European network commonly supported," he said.

Global Implications

It is not just U.K. researchers who would be affected by the United Kingdom exiting the Horizon Europe program. Since the Brexit vote in 2016, scientists from EU nations working in the United Kingdom have faced uncertainty, particularly younger researchers without the established ties to secure their long-term status. According to data published in March by *Times Higher Education*, the proportion of EU citizens in their thirties within the U.K. university workforce has been declining for the past 4 years (bit.ly/workforce-decline). Continued uncertainty over the United Kingdom's status in Horizon Europe could exacerbate this trend.

"Many of the common societal challenges currently being addressed by international research teams such as climate change, ensuring food security, or finding cures for diseases do not respect geographical or political boundaries."

Javier Pardo Díaz, director of science policy at the Society of Spanish Researchers in the United Kingdom (SRUK), said the number of SRUK members has decreased considerably since Brexit. In a 2021 SRUK survey, 94% of respondents stated that the United Kingdom's exit from the EU will affect their lives, and 65% said the United Kingdom has lost attractiveness. Pardo Díaz said that U.K. association with Horizon Europe would enable EU researchers to keep moving to the United Kingdom through the Marie Skłodowska-Curie Actions funding program for doctoral and postdoctoral training. "This is relevant if taking into account that the U.K. has some of the most prestigious universities and research centers in the world," he said.

Helen Glaves, president of the European Geosciences Union, said it is important to avoid "artificial barriers" that prevent exchange of knowledge and expertise between researchers in the United Kingdom and the rest of Europe. "For decades, the U.K. has been part of the wider European landscape that has been a world leader in cutting-edge research and innovation," said Glaves, a data scientist and oceanography researcher at the British Geological Survey. "Many of the common societal challenges currently being addressed by international research teams such as climate change, ensuring food security, or finding cures for diseases do not respect geographical or political boundaries; they require a common effort to find a solution that benefits both humans and the planet."

By **James Dacey** (@JamesDacey), Science Writer

Supervolcanoes Linger a While, Then Rush to Erupt

Parinacota is not a supervolcano, but it sits close to the quartet of volcanoes in the Oxaya Formation of northern Chile. Credit: Dan Lundberg/Wikimedia, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Along the western flanks of the Central Andes, million-year periods of quietude were followed by moments of enormous activity. Magma lingered deep in the crust for a million years or longer, allowing layers of granite to form above it. The magma then surged upward over just a few decades and erupted as a supervolcano—an act that played out four times in 3 million years.

That scenario, published in *Nature* and developed through a study of crystals embedded in layers of volcanic rock, provides a revised model of how supervolcanoes erupt (bit.ly/magma-chamber).

"Prior studies of supervolcanoes favored a model where crystals were stored for hundreds of thousands of years in a magma mush—a material that contains melt yet is too rich in crystals to erupt," said Catherine Annen, a geologist at the Institute of Geophysics of the Czech Academy of Sciences who was not involved in the new study but has previously collaborated with some of its authors. Instead, the study showed that crystals are stored in solid rock and mix with the rising magma shortly before eruption.

"We wanted to understand the timescales and dynamics for the assembly of magma reservoirs prior to supereruptions," said Stephen Sparks, a study author and a professor emeritus at the University of Bristol School of Earth Sciences. "Our study is part of an emerging understanding of the conditions that lead to supereruptions, which may ultimately help find sites with high risk of future supereruptions."

Volcanic Crystals in Cold Storage

Sparks and his coauthors examined material extracted from oil company drill holes in the Oxaya Formation in northern Chile. The region includes four previously known supervolcanoes (defined as volcanoes with eruptions that deposit at least 1,000 cubic kilometers of rock): Cardones, Milonos, Oxaya, and Poconchile. They erupted at roughly million-year intervals, beginning with Poconchile about 22.6 million years ago.

In the laboratory at the Scottish Universities Environmental Research Centre, the team isolated crystals of zircon and sanidine, a potassium-rich form of feldspar, from a layer of volcanic rock known as ignimbrite. Among other techniques, the researchers used a laser to melt sanidine crystals that averaged about 2 millimeters in diameter, extracted argon from the resulting gas, and then compared the ratio of the isotopes argon-40 and argon-39.

"The headline is, we got argon-argon ages from these samples, spanning several million years," said Marissa Tremblay, a noble gas geochemist at Purdue University who participated in the analysis. "That tells us a lot about how these magmatic systems that lead to supervolcanoes had to evolve."

> **"The study of these crystals shows that the magma chamber that directly feeds the eruption had a short lifetime of no more than a few centuries."**

In particular, the dating techniques revealed that the crystals, which formed in magma, spent a long time in "cold storage," at temperatures no higher than 470°C. "We interpret that to mean they were part of a pluton," a mass of granite in the middle to upper layer of the crust that built up over a period of a million years or longer, Tremblay said. "But at some point [the crystals] had to be reentrained with a magma and then quickly erupt with that magma—over a timescale of years to decades."

"The study of these crystals shows that the magma chamber that directly feeds the eruption had a short lifetime of no more than a few centuries, so that large volumes of magma must have been emplaced very rapidly in the upper crust," said Annen.

Recipe for a Supervolcano Eruption

The team verified the findings with new mathematical models, then devised a scenario for the eruption of a supervolcano.

The zircon and sanidine crystals began forming more than 4 million years before the initial Poconchile eruption. They were emplaced at fairly shallow depths, where they cooled with the surrounding rock to form granite, supplemented by drizzles of fresh magma from a chamber far below.

Instabilities in the overlying rock led to the formation of wide dikes that allowed the magma to flow upward to form a chamber near the surface, melting and incorporating some of the granite along the way. "We propose rapid assembly of the magma bodies in the upper crust, which destabilized plutonic roof rocks just prior to and during the supereruptions," said Sparks.

The shallow magma chamber formed quickly, then erupted, creating a wide, relatively shallow depression known as a caldera. "A supervolcano doesn't have the typical cone shape like you'd see if you asked a kid to draw a volcano," explained Tremblay. "A supervolcano is so catastrophic that it leaves a big hole in the ground."

After each eruption, with the shallow chamber empty, the process began again, with magma creating a new pluton, then quickly forming a new shallow chamber and erupting. The sequence ended with a final eruption 19.6 million years ago.

No one knows when to expect the next big hole in the ground. Supervolcanoes appear to occur once every 20,000 or so years; the most recent, Taupō in New Zealand, occurred about 27,000 years ago. The new study's findings could help guide geologists as they hunt for the likely sites of these future catastrophes.

By **Damond Benningfield,** Science Writer

New USGS Director: Partnerships Are Our Superpower

On 15 August, David Applegate was sworn in as director of the U.S. Geological Survey (USGS). Applegate, who had been exercising the delegated authority of the director since January 2021, is a natural hazards scientist who has been with the Survey for 18 years.

At the ceremony, U.S. Secretary of the Interior Deb Haaland said, "As people, wildlife, and ecosystems face the impacts of the climate crisis, David's long and impressive tenure will continue to be essential to ensuring that the department continues to be an international leader in developing the climate science needed to understand the Earth's past, present, and future climate."

Applegate spoke with *Eos* after his confirmation, reflecting on how the agency has evolved over the past 2 decades and his vision for the agency in the future. The conversation, below, has been edited for clarity and length.

Eos: *How did it feel to receive the nomination, and what are you feeling now that you have been sworn in?*

Applegate: It was tremendously exciting to take on this role, not just as one who is exercising delegated authority but to occupy it for real. I think it didn't become real to me until the opportunity to be sworn in by Secretary Haaland. That truly was the honor of a lifetime.

When you're exercising the delegated authority, you are laying the groundwork for who will be coming in as the next director, trying to address as many issues as you can and [set] the table, as it were. But it is different than when you're in the role itself. I already felt a deep sense of responsibility for the organization, but now that is doubly the case.

Partnerships are what enable us to deliver on our mission and to ensure that our science is what is needed to address a wide range of issues.

Eos: *You've spent over a year setting the table. Now you're sitting at the head of the table. What do you hope to accomplish during your tenure as director?*

Applegate: My big focus is on ensuring that we are delivering our science to those who need it the most. We have a wonderful mission at the USGS. We bring science to bear on an incredible array of complex environmental, resource, and hazard issues that are facing society. For us, the key is to be able to have the outlets…so that the science can be put to work.

Eos: *Are there particular programs or initiatives you're really looking forward to?*

Applegate: We've been able to see some very significant investments in our science and in our foundational data collection through the Infrastructure Investment and Jobs Act (Bipartisan Infrastructure Law): almost half a billion dollars' worth of investment for us both to collect foundational data and also to then do the analysis and have new facilities in which to undertake our science. In particular, the investment is focused on understanding critical mineral potential and the role that that plays in supply chains for clean energy.

And there is investment in our 3D elevation high-resolution topography in geophysical data collection and in geologic mapping. This is an incredible shot in the arm for our long-standing partnership with the state geological surveys, as well as with the universities preparing that next generation of geologic mappers.

Eos: *In addition to the Bipartisan Infrastructure Law, are there ways in which the Inflation Reduction Act of 2022 will be another shot in the arm for some USGS projects?*

Applegate: We were very pleased to see there's about $23.5 million worth of investment in our 3D Elevation Program. This is going to help move us forward in completing

U.S. Secretary of the Interior Deb Haaland (left) swears in David Applegate as director of the U.S. Geological Survey. Credit: U.S. Department of the Interior, Public Domain national coverage of high-resolution topography data, which is one of those foundational data sets that enable an incredible array of applications. It was tremendous to see that in the bill.

We are also seeing our resource and hazard assessments being tapped into to help support a number of the other Department of the Interior bureaus. For example, the work that is being enabled with respect to orphan oil and gas wells and with respect to ecosystem restoration requires a lot of scientific understanding to prioritize and effectively undertake, so it's great to see our science getting put to use in that regard.

Eos: *What new partnerships are you hoping to pursue? What existing partnerships do you hope to strengthen?*

Applegate: I like to say that partnerships are the superpower of the USGS. They're what enable us to deliver on our mission and to ensure that our science is what is needed to address a wide range of issues. We have the regional climate adaptation science centers, which directly support the decisions that managers at the state and national levels face in addressing a changing climate. And we have long-standing university partnerships across our mission areas that help us to engage that next generation.

And then one of our strongest partnerships within the federal family is our longstanding partnership with NASA. I had the opportunity to participate in the formal transition of operational control for Landsat 9 from NASA to USGS.

NASA had launched the satellite and made sure that all systems were go, and they have now handed it over to the USGS to fly it, we hope, for decades to come. That was an exciting moment. It comes right on the heels of celebrating 50 years of Landsat data and all of the incredible applications that it has made possible.... It's a poster child for making data free and openly available.

Looking forward, we see this in the context of the rapidly developing capabilities with other countries as well as in the private sector.

Eos: *What challenges do you anticipate as you move forward?*

Applegate: One of the key things that we need to do is to rebuild our workforce, particularly to support those who support our science and all of those who are engaged in the business of science. How do we bring on board that next-generation workforce, retain them, and give them a workplace environment that is respectful and inclusive and where they can thrive? That is central to our ability to deliver our science to those who need it most, to be able to reach underserved communities, to be able to engage with Tribes and other users for whom we need to ensure that the science is broadly applicable and in a form that they can use.

"We're trying to harness that energy and turn that into tangible improvements in the DEIA space. It's absolutely essential for our future health and viability as an organization."

Part of that is having a workforce that has those lived experiences and is able to help to deliver on the mission. In the area of diversity, equity, inclusion, and accessibility (DEIA), we have more than a generation's worth of good intentions, and yet we have not seen dramatic changes from a workforce standpoint. We have a tremendous amount of energy at our grassroots and across all of our science centers. We're trying to harness that energy and turn that into tangible improvements in the DEIA space. It's absolutely essential for our future health and viability as an organization.

Eos: *You've been at USGS for 18 years now in a variety of roles within the organization. How have you seen the agency evolve, and how would you like to see it keep progressing in the future?*

Applegate: It's actually 18 years and one summer! I got to spend the summer after college as a part of the [National Association of Geoscience Teachers]–USGS summer internship program and had the wonderful opportunity to be at our Geologic Hazards Science Center in Golden, Colo. I loved the mission of the agency. I loved the idea of applying the science and putting it to work on these critically important issues.

We have seen an increasing emphasis on "How do we make the science real to people?" That's been very important to us in our hazards mission, which is where I've spent the past 18 years.

One of the areas that we've focused on is risk. We've done so much over the years to understand the hazards and to be able to deliver real-time situational awareness. But people don't live in hazard space. They live in the space of how those hazards impact them. Across our mission areas, we've worked to strengthen our partnerships with the social sciences. Through these efforts, we can increase our own expertise, draw on extensive external partnerships, and engage with people throughout the process. I'm excited to take that approach and really expand that across the bureau.

We're not a typical geological survey, right? We're a geological and biological and hydrological and mapping entity. And it is that combination of disciplines that enables us to tackle these complex societal issues.

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

Credit Where Credit Is Due

Credit is the currency of science. Scientists are evaluated and promoted in their jobs and professional communities on the basis of their *recognized* contributions to science. Unlike a financial contribution, a scientific contribution is difficult to measure. Traditionally, credit for scientific contributions has been given through authorship and citations in scientific literature; through awards and the naming of geographic features, instruments, and methods; and through other honorifics. However, these practices do not capture the breadth and depth of the contributions by all actors in modern, open science.

As science becomes more complex, it is increasingly challenging to recognize (and hold accountable) the many people taking part in projects that may involve detailed planning and funding efforts, sophisticated data collection and analysis techniques, custom software development, integration of data from multiple sources, and complex workflows involving machine learning and other sophisticated methods.

Today there is increasing recognition among many scientists and scientific institutions that fostering science that is more inclusive, transparent, and reproducible requires that we support wider designation of credit *everywhere* it is due—and to do that, authorship roles and other contributions must be more clearly delineated.

In 2017, AGU adopted the Contributor Roles Taxonomy (CRediT) for use in its peer-reviewed journals, in part to increase "transparency around contributions in scholarly research" [*Hanson and Webb*, 2018]. This approach was supported in a leading opinion by *McNutt et al.* [2018]. Earlier this year, CRediT, which "describes 14 roles that represent the typical range of contributors to scientific scholarly outputs, and that can be used to enable recognition and facilitate transparency," was published as a national standard. This standardization is a great advance in recognizing the many roles that factor into the production of publications, but what about authorship and credit for other research artifacts, such as data, code, algorithms, methods, and samples?

The Earth Science Information Partners (ESIP)—a community of Earth and data scientists focused on the collection, stewardship, and use of Earth science data, information, and knowledge in response to societal needs—created the Research Artifact Citation cluster to examine all aspects of referencing and crediting the artifacts of research. The cluster examined whether the CRediT taxonomy, and others, could be applied across a broad range of research artifacts. Through guided sessions and structured discussions, we learned valuable lessons about these taxonomies—including that no one taxonomy suffices in all cases—and about how different communities approach crediting and attribution.

Mapping Out Who Does What

Citation is a credit mechanism that was developed for publications, but various contributions may need to be credited differently for other research artifacts. People often suggest using a model styled after film credits, in which certain key roles—lead actors, directors, and producers, for example—are listed at the beginning of a movie, and numerous supporting roles, from camera operators to caterers, are listed at the end. What may not be evident to viewers not in the movie industry is that the order, prominence, number, and categories of the roles listed are determined in a highly negotiated process involving agents, unions, contracts, and other factors. In much the same way, finding an effective way to designate credit and capture the complexities of different roles in scientific research—and to share this information in a simple way—continues to be a challenge.

Over about 18 months beginning in spring 2020, the ESIP cluster conducted multiple working meetings that brought together dozens of researchers, software developers, and data professionals for discussions of how the myriad roles involved in producing research artifacts could be appropriately credited. We took an exploratory approach in which early meetings refined the questions explored in subsequent meetings.

Initially, participants examined whether the 14 roles included in CRediT (and listed in the acknowledgments at the end of this article) could be applied to appropriately denote credit for other research artifacts, including data, software, learning resources, physical samples, and semantic resources (e.g., scientific categorizations, taxonomies, and ontologies). We also considered the prominence of each role, whether it is akin to authorship of a publication (like top billing in movie credits) or more like a contribution that would be included in formal acknowledgments or in metadata or documentation connected to the artifact (like the fine print at the end of a movie).

From that effort, we determined that defining the research artifact in question is essential for understanding all its component roles and for properly assigning credit, yet even that can be quite difficult. For example, a "model" can be many different things—a conceptual diagram, a climate simulation, a machine learning approach, or something else—each of which can involve different sets of contributors and types of recognition. Even when one can define the artifact clearly, our discussions revealed that CRediT does not apply well for artifacts other than articles. Some roles may be missing from the taxonomy, whereas others may be too vague. For example, CRediT includes a very broad category for software contributions, which is not very helpful when defining distinct roles within software development.

Different Communities, Different Vocabularies

We began to explore what roles are missing from CRediT and what other credit taxonomies might be useful. This exploration was partially based on the work of *Habermann* [2021], which provides comparisons, or "crosswalks," of how concepts and contributor roles are described differently depending on context and across several approaches, including CRediT, the Contributor Role Ontology, the Data Documentation Initiative, and others. For example, roles like "data quality control" or "data validation" are interpreted very differently with respect to simulation data compared with direct observational data. Similarly, the role of "collector" is critical for physical samples but irrelevant for software.

It was becoming clear that no one basic credit approach or taxonomy would suffice for even a plurality of artifacts.

Although we initially thought we would be able to generalize credit mechanisms for certain types or classes of research artifacts, we found that not only does production of different types of artifacts involve different roles but also different research communities have distinct cultures and approaches for recognizing those roles. For example, the semantic web community, which works to describe web content formally in a machine-interpretable way, has established consistent ways to credit contributions to ontologies and definitions by explicitly labeling terms with persistent identifiers for the authors and editors who work on them. On the other hand, communities that collect and curate physical samples—such as ice cores or biological specimens—often have distinct approaches to acknowledging credit because from discipline to discipline, these activities can involve very different methods and roles in the field and the lab.

It was becoming clear that no one basic credit approach or taxonomy would suffice for even a plurality of artifacts. So we decided to narrow our focus strictly to data citation to see whether we could identify a relevant taxonomy or guideline describing the primary role of data authorship.

This task also proved difficult. We asked participants to assign weights to the importance of 36 roles listed in the Contributor Role Ontology, which expands on the roles included in CRediT, for different types of data. We found that the importance of various roles could vary significantly depending on the type of data. For example, participants weighted study design and protocols very highly for data collected during a field campaign, whereas data integration and quality assurance rose to the top for satellite remote sensing data.

There were, however, some commonalities across data types. For example, in almost all cases, participants agreed about the importance of those who develop the initial idea for, or conceptualize, a data collection effort. This is in keeping with the general ESIP definition of data authorship: "the people or organizations responsible for the intellectual work to develop a data set" [*ESIP Data Preservation and Stewardship Committee*, 2019]. There was also general agreement that some roles, although important, do not rise to the level of data authorship. These include roles like providing funding and designing instruments used in data collection and analysis, as well as the many unseen roles of infrastructure support and maintenance.

A Case-by-Case Basis

Our main takeaway from the meetings and discussions was that designating credit and attribution is extremely situational and contextual.

This observation is not entirely new. Who should be considered an author of a scientific article and the order in which authors are listed are issues that have been debated for centuries—and approaches vary immensely across disciplines. However, our work revealed that when we consider the wide range of research activities conducted and artifacts produced today, the complexities multiply. Our work also reinforced that citation is but one of multiple mechanisms that scientists should consider in recognizing the contributions and roles of everyone involved in producing valuable scientific artifacts.

Although we did not find a taxonomy that applied well across scientific disciplines or types of research artifacts for designating credit, several consistent lessons emerged from our work that serve as recommendations. It is very helpful, for example, for a

Opposite: girafchik/Depositphotos.com

Fig. 1. Defining contributor roles and attributing credit for various aspects of a project reveal a complex network of interacting participation. Here we see participants and their roles in the project leading to this article. Credit: Ruth Duerr

broad group of team members to identify the various roles in a project carefully and deliberately and to assess each role's significance early in the research process. Teams should think about the following questions: Who is contributing to the project and how? Are those contributions significant enough to warrant authorship? If not, how else could people and organizations be recognized for their work?

Second, taxonomies can provide useful guidance when addressing those questions, potentially helping key participants recognize more fully the breadth and impact of supporting roles, but they are never definitive. The specific context of a project must be considered, including whether roles are being parsed or aggregated to provide a fair representation of contributions. As part of this effort, it is important to decide how roles will be formally recorded, whether, for example, as citations or acknowledgments in a publication or in the documentation of an artifact. Someone who developed data collection protocols for a large, complex field campaign might be considered an "author" of the resulting data sets, whereas in a relatively simple field experiment using established methods (i.e., the method could be cited), that person may be listed only in the acknowledgments. Meanwhile, the people who actually collected the data might be mentioned in acknowledgments, or the names of individuals responsible for particular observations might be embedded in the data themselves.

In any case, in the interest of promoting transparent and reproducible science, it is important to formally document contributions whenever possible using unique persistent identifiers so that the research community can trace the provenance and impact of contributions. This documentation is also important so that credit for work, still the prevailing currency of science, follows those who performed it.

Looking Beyond Author Lists

The culture of how we value different activities and contributions in science—and thus how we evaluate individuals for promotions, awards, funding, and more—is evolving [*Teperek et al.*, 2022]. These evaluations must go beyond just assessments of the articles a researcher has written. Moreover, in evaluations of research artifacts other than articles, the contributions of people beyond just those listed as authors or creators should be considered. Author lists do not tell the whole story of how valuable scientific products came to be.

A narrative description of contributions could be more useful than a traditional curriculum vitae with a list of publications in facilitating fairer evaluations. Better yet, a network graph can show how a scientist contributed to the production of various data sets and software that, in turn, fed into subsequent articles and other data sets. We believe more holistic and interconnected approaches like these help make science more inclusive and transparent.

We hope the work of the ESIP Research Artifact Citation cluster to date and the observations presented here prompt further conversation in the scientific community. Structured discussions will continue in both the cluster and a new AGU-led community of practice that's working with the Research Data Alliance to consider how to assign credit transparently for large, complex data collections. Both groups welcome public participation. Ultimately, outcomes of these ongoing discussions and efforts will help give credit where it's due and help the practice of science evolve to become more robust, accessible, and trusted.

Acknowledgments

This article resulted from the work of scores, if not hundreds, of people. The ESIP Research Artifact Citation cluster worked collectively to determine the questions we pursued and the methodology we used. We entrained scores of people to contribute to our workshops both online and in person. The work was truly a community effort.

Ironically, *Eos* guidelines limit us to only five authors in the byline, but more than a dozen people contributed directly to writing this article. We capture them in Figure 1 and the list below based on the Contributor Roles Taxonomy (CRediT). Names under each role are listed alphabetically, with organizational contributors at the end.

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Deploying Community Water Solutions with People, for People

Water is the lifeblood of human and environmental health and thus of civilization, the global economy, and sustainable development. Yet access to water is still largely taken for granted by people at all levels, from individual water users to businesses and governments. Problems related to water accessibility, supply stability, and use—as well as inaction in tackling problems—often go unaddressed. Moreover, typical water security indicators that measure water availability and infrastructure in aggregate at state or regional levels have at times served to obscure disparities in security at local consumer levels [*Young*, 2021].

Neglecting the largely invisible social and environmental value of water and water availability—in addition to its economic value—not only can directly harm the individuals, communities, and businesses who must deal with water shortages and price increases but also can translate into diminished ecosystem services that depend upon water. Wetlands, wildlife habitats, and urban green spaces, for instance, can serve as public amenities. As climate change, urbanization, and development continue, and in many places accelerate, existing freshwater supplies are being stressed by, for example, increased aridity and overuse.

It is thus becoming increasingly important to identify opportunities where interventions can help to resolve water security issues at socially, economically, and culturally relevant scales.

When conventional governmental and policy channels for effecting change are exhausted or prove ineffective or unnavigable, locally focused and organized actions can potentially provide solutions and fulfill community needs. A collaboration between Global Water Works (GWW), a U.S.-based nonprofit organization that connects people in need of water solutions with solutions providers, and the World of Water (WOW) Action Forum, a resident-led collective in India that mobilizes people to implement local water conservation measures, is providing powerful examples of how water solutions can be successfully implemented in urban communities.

Here we present a case study in which residents, through individual and collective action, transformed water provision pathways in their community. This story represents one of many documented by WOW in its online collections of videos, podcasts, and blogs. Although each case is unique, reflecting distinct local risks and opportunities, common guiding principles for identifying these opportunities and addressing

When Bengaluru apartment residents can't get enough water from on-site wells, tanker trucks like this one bring in water to fill the additional need—for a price. Credit: Ganesh Shanbhag water risks have emerged—principles that can be transferred to other communities facing similar problems.

How One Person Made a Difference

Devi Gopalan Joseph lives in Victory Harmony, an 11-year-old high-rise apartment building with 99 units in northern Bengaluru, India. The water supply for the complex has historically come from a combination of its borewells, which source local groundwater, and tanker trucks that transport river water from distant sources to the building. When Devi first took an interest in her building's water supply in September 2021, the building required a monthly average of 150 tankers supplying 1.8 million liters of water to supplement the dwindling supply from its wells.

Bengaluru, the largest city and capital of the southern Indian state of Karnataka, is home to 12.3 million people. It is one of the fastest growing cities in the world, thanks to influxes of people from rural areas searching for employment and the growth of technology and other water-intensive industries—and water demands there are growing along with the population.

Since the 1990s, half of Bengaluru's water supply has come directly or indirectly (via water tankers) from borewells tapping deep groundwater aquifers [*Tomer et al.*, 2020]. The city's remaining water needs have been met by pumping water from the Kaveri River, more than 125 kilometers from the city. Groundwater withdrawals deplete slow-to-recharge aquifers, whereas transporting river water to the city incurs costs from transportation and subsequent distribution, fuel and energy use, and infrastructure installation and maintenance, such as installing the pumping and water circulation systems, all of which also contribute to greenhouse gas emissions.

A better alternative to these sources is available. The 900-square-kilometer city receives, on average, 960 millimeters of precipitation annually. Collecting and harvesting this rainwater represent a viable approach to meeting water consumption needs and provide additional cobenefits, such as reducing urban stormwater flooding.

Devi had long been a proponent of water-saving methods in her home and apartment complex. However, advocating similar behaviors among her neighbors using traditional awareness-building methods about the environmental and health benefits of water conservation proved ineffective. As Devi persisted in engaging with her fellow residents about water consumption, she found a common theme: Water was scarce, and residents were frustrated with the resulting price increases, especially given that their regular payments covered only routine borewell maintenance activities, not structural improvements that would result in more water reaching their households. In addition, as water became scarcer, residents were required to pay an additional rupee per square foot of their apartment for their water access—an additional 1,200 rupees (US$15.67) per month for a 1,200-square-foot apartment, for example.

Meanwhile, Devi also came across social media posts describing rainwater harvesting (RWH) technologies, including articles and blog posts by Ganesh Shanbhag (a coauthor of this article), who works at WOW. RWH involves the collection, storage, and treatment of rainwater from rooftops, terraces, courtyards, and other impervious building surfaces for on-site use [*Campisano et al.*, 2017]. It has been estimated that during the monsoon season in Bengaluru, RWH can reduce water supply burdens by 15%–20% [*Umamani and Manasi*, 2013].

Devi reached out to Shanbhag and other local water activists and practitioners. WOW guided her toward a science-backed technology for treating rainwater as it descends through an RWH system. This water can then be stored in underground storage tanks in the short term as well as being diverted to aquifers for groundwater recharge in the long term.

Devi devised a strategy to persuade her neighbors of the cost efficiency of RWH, taking on the title of the "adopted mother" of her apartment complex to evoke feelings of care and mindfulness associated with community-centered approaches. She also mobilized eight other adopted mothers, each of whom was assigned to go door-to-door to nine apartments in Victory Harmony, introducing RWH to her neighbors and debunking misconceptions. Among the misconceptions the mothers encountered were that filtered rainwater was of low quality, that introducing the technology would be costly, and that RWH could not be retrofitted to older buildings.

The adopted mothers thus demonstrated an economic value proposition that was directly relevant to their fellow residents'

The pipes seen here are part of the rainwater filtration system at the Victory Harmony apartment complex. Credit: Ganesh Shanbhag.

concerns, showing them how a small initial investment and some simple changes in the ways the building obtained and used water could result in substantial financial savings and help to restore the water supply from their borewells. The proposition motivated residents to change entrenched consumption patterns, and the adopted mothers secured consent from all 99 households to implement an RWH system, which was installed and operational by November 2021. Working with a vendor vetted and introduced to them by WOW, the adopted mothers also installed smart meters to measure the water collected via the RWH system.

The timing worked out well. November is past the peak rainy season of the year, but November 2021 was a much wetter than average November in Bengaluru. Rainfall exceeded the monthly average by more than 300%, and in that month alone, the RWH system harvested 350,000 liters of water for direct consumption. In addition, the system sent water to the building's borewells, helping replenish them and meet the consumption needs of the residents. As a result, rather than needing 150 tanker loads of water to be delivered that month, residents required only 20. The building saved more than 50,000 rupees (US$653) in tanker expenses—money that could be put toward recouping the cost of the RWH system over a few years.

Groundwater recharge pits allow rainwater to refill borehole wells that supply water to residents in Bengaluru. Credit: Ganesh Shanbhag

Common themes and characteristics emerge from investigating successful examples of user-led water solutions like Devi's. Solutions and technology providers, as well as other individuals and organizations pushing for water conservation, can apply these lessons to implement successful water management strategies and to develop value propositions for their own products and contexts.

Think Locally, Act Locally

Water consumers at the local level are best positioned to identify the water problems that are integral in their lives, well-being, and culture. Indeed, local user-led problem identification is critical to initiating successful deployments of water solutions. This identification, in turn, can help build awareness of local and culturally relevant issues and generate buy-in for technologies and solutions among other affected consumers.

With their intimate understanding of the impacts of water scarcity and how inaction can cost them, financially and otherwise, local users are also best able to identify, judge, and validate the unique value propositions and potential benefits of technologies in their communities. This understanding affords local actors the language and legitimacy within their communities to pursue consensus building and investments in community solutions such as RWH.

At Victory Harmony, in addition to highlighting the fundamental health concerns of water scarcity, the adopted mothers framed practical arguments through a grassroots, socially informed lens, broaching the issue with their neighbors from an economic perspective: The cost-effectiveness and savings of their proposed system underscored its accessibility and viability. By making the financial argument for RWH, Devi, in effect, made the "value" of water visible, resulting in support for not only a reliable solution to the apartment complex's water problems, but also one with supplemental environmental benefits (e.g., bolstering the vitality of the local groundwater table).

The value of individuals thinking and acting locally has been exhibited not only in Devi's case but also in many other efforts supported by WOW and GWW, including, for instance, at a residential building in eastern Bengaluru and a home in southern Bengaluru. In these cases, recently installed RWH systems have also provided residents facing water scarcity with needed resources and cost savings.

Collaborate on the Demand Side

Close collaboration among multiple active parties in a local setting is vital for progressing from problem identification to information sharing and promoting science-based, culturally appropriate awareness, then to solution development, and, finally, to solution implementation. These active parties take on the role of "water connectors" within their communities, possessing the contextual and cultural insights needed to determine which technologies and solutions would be more effective and appealing to local water users.

With their intimate understanding of regional conditions, local users are best able to identify, judge, and validate the unique value propositions and potential benefits of technologies in their communities.

Water connectors like Devi and her fellow adopted mothers were effective in part because of the frequent natural exchange of information between them and the rest of the Victory Harmony residents, and because they themselves were water users suffering the consequences of local water problems. But also, they were supported by a network of other water connectors via WOW, including leaders in Bengaluru's water sector who facilitated community-level information sharing. This network also included local domain experts equipped with the technical and cultural proficiency needed to connect water users with the right stakeholders and with accountable solutions providers who can offer quality solutions at reasonable prices for each given situation.

Devi's local domain experts were the members of the WOW network. These experts also validated her community's water scarcity issues by observing their need

The four roles on the ring of this diagram represent the parties essential for creating an effective and conducive solutions environment in which the three guiding principles discussed in this article can be applied.

for water tankers to meet consumption requirements, and they helped convey the benefits and appropriateness of RWH technology in her context. They empowered Devi and the adopted mothers with technical knowledge, and their support added weight and legitimacy to the group's efforts to secure the buy-in needed from the Victory Harmony residents to invest in and install water collection and transportation systems on the roof.

Devi's example makes clear that action-focused collaboration among various demand-side water connectors helps raise awareness of the value of water in people's lives and in society more broadly, which can then help convince water users to adopt appropriate technologies to solve community water problems.

Craft Messaging to Illuminate the Value of Water Solutions

Effecting behavioral change by clearly communicating the financial and cultural value of water to consumers and devising actionable, agile, and locally adaptable technological solutions help ensure the long-term sustainability of both the solutions and the water supplies.

In successful deployments of sustainable technological solutions, changes in behavior and long-term practices result from a multistep process. First, some event or sense of urgency catalyzes local actors and connectors to act to address their water problems. Once their water problems are validated and they are empowered with the necessary information on available solutions, local actors and connectors can develop effective messaging about the value of water and water solutions with which to lobby peer consumers in their community to rethink and change long-held assumptions and practices.

As demonstrated in Devi's case, a good first step toward developing a meaningful and appropriate value proposition for a community is to converse with and listen to people experiencing water problems, and to identify common concerns and complaints that can be addressed through solutions. The second step is to hone messaging that succinctly acknowledges these concerns and states how a specific solution can help alleviate them.

This messaging can also be used to lobby government agencies and organizations, including building management, for help acquiring the technology and funds needed to implement a water solution in the community.

A Recipe for Success

The principles illustrated by Devi's case and others provide an effective blueprint for deploying water solutions and technological innovations in cities like Bengaluru, in the immediate term and beyond.

Knowledge networks helping in such deployments, like WOW, are continuing to grow. WOW is expanding its mission to other cities such as Chennai and Trichy, adapting the guiding principles outlined here to local contexts. With more research and data from additional case studies, these principles can be updated and refined, eventually helping people and communities across India and elsewhere to address the global problem of water scarcity on local scales.

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Geoscientists Can Help Reduce the Threat of Nuclear Weapons

While we all recognize that global warming threatens humanity, the effects of nuclear war pose an even graver threat to the global population.

The immediate devastation from nuclear blasts and subsequent fires and the lasting harm from nuclear radiation have, of course, been demonstrated tragically. But a nuclear war would also produce nearly instantaneous climate change that among other effects, would threaten the global food supply. Even a regional nuclear war could threaten civilization globally and condemn innocent bystanders to famine, including inhabitants of the country that initiated the conflict. In effect, a nuclear attack would be the action of a suicide bomber [*Robock and Toon*, 2012].

The scientific community, particularly physicists and geophysicists, has a special relationship with the problem of nuclear weapons. We have performed the research and developed the technology that created the weapons, and we have studied their effects. But there is also a long history of scientists opposing use of the weapons and warning of the outcomes in the event they are used. Today, as nuclear arsenals and the plausibility of their use are growing anew, we argue that it is again time for physical scientists to advocate for steps that reduce the nuclear threat. A coalition is working to do just that.

Fires ignited by the atomic bomb attack on Hiroshima, Japan, on 6 August 1945 pumped smoke and soot into the upper troposphere and lower stratosphere and created the pyrocumulonimbus cloud seen in this photo, which was taken more than 3 hours after the attack. Credit: U.S. Army

The Growing Threat

The existence of nuclear weapons means that they can be used, and this threat is getting more severe as the number of possible scenarios leading to nuclear war rises. Currently, there are more than 9,000 nuclear warheads in the active military stockpiles of nine nations, with more than 90% of those in Russia and the United States. Nearly 2,000 warheads are on alert status, ready to launch within minutes of an order.

New technologies threaten the abilities of governments to control and secure nuclear weapons. A cyberattack on nuclear weapons control systems, for example, could create false warnings of launches or perhaps even initiate real launches. Even before the emergence of cyberthreats, there were many instances of near launches by technical or human error. And it was only because cooler heads prevailed that nuclear weapons were not used deliberately during the Cuban Missile Crisis of 1962 or amid the Vietnam War when military leaders urged their use [*Ellsberg*, 2017].

The nuclear arms control regime has been weakened in recent years with the termination of the Anti-Ballistic Missile Treaty and the Intermediate-Range Nuclear Forces Treaty between Russia and the United States, the withdrawals of those countries from the Treaty on Open Skies, and the withdrawal of the United States from the Iran nuclear deal. These actions are culminating in an emerging nuclear arms race, with most nuclear powers modernizing their arsenals. The planned trillion-dollar, multidecade modernization of the nuclear arsenal in the United States would commit the country to nuclear weapons for most of this century.

In addition to immense physical damage to both built and natural environments, as well as lingering radioactive fallout, a nuclear conflict would cause rapid changes in Earth's climate.

Nuclear Climate Change

In addition to immense physical damage to both built and natural environments, as well as lingering radioactive fallout, a nuclear conflict would cause rapid changes in Earth's climate. Smoke from firestorms ignited by attacks on cities and industrial areas would rise into the stratosphere and persist for years [e.g., *Yu et al.*, 2019]. This smoke would block sunlight, causing global cooling [*Robock et al.*, 2007a; *Coupe et al.*, 2019], and it would lead to stratospheric ozone depletion that would enhance the amount of ultraviolet radiation reaching Earth's surface [*Bardeen et al.*, 2021].

The original suggestions by *Turco et al.* [1983] and *Aleksandrov and Stenchikov* [1983] of "nuclear winter" following a nuclear war, which were based on very simple climate models, have been supported strongly by recent work using modern high-resolution general circulation models to simulate and predict its effects [*Robock et al.*, 2007a; *Coupe et al.*, 2019]. Even a regional nuclear war, such as between India and Pakistan [*Robock et al.*, 2007b; *Toon et al.*, 2019], in which less than 3% of the world's nuclear weapons were detonated, would suddenly decrease the average global temperature by 1°C–7°C, precipitation by up to 40%, and sunlight by up to 30%. No matter the scale of the soot injection into the skies, the multiyear lifetime of smoke in the stratosphere means that the effects on climate would last a decade, with the largest impacts continuing for more than 5 years. Such a conflict would decrease crop production to an extent that it could seriously threaten world food security and even trigger global famine [*Jägermeyr et al.*, 2020; *Xia et al.*, 2022].

Physical scientists, including geoscientists, can offer expertise and insight into the hazards and consequences of nuclear conflict—and can be influential voices for nuclear threat reduction.

A Safer Path

Many measures can be implemented to reduce the likelihood of using nuclear weapons, including steps by our country, the United States, that in our view would make the country and the world safer. For example, we can adopt a no-first-use policy, meaning that the United States would never start a nuclear war but, rather, only respond to a nuclear attack. We can also eliminate the launch-on-warning option, which pressures a presidential decision on whether to launch a counterattack within 5–10 minutes (and is thus particularly vulnerable to launches by error), and we can eliminate presidential sole authority to launch nuclear weapons. This most fateful decision should not be made by just one person [*Perry and Collina*, 2020]. In addition, we can and should restart the arms reduction negotiations between the United States and Russia that were initiated by President Ronald Reagan and Soviet leader Mikhail Gorbachev in the 1980s. These negotiations led to multidecade reductions in nuclear arsenals, but that progress has recently stalled.

We believe that the ultimate solution to the problem of nuclear weapons is to ban them globally. In 2017, the International Campaign to Abolish Nuclear Weapons led the effort to have the Treaty on the Prohibition of Nuclear Weapons signed at the United Nations. The campaign was awarded the 2017 Nobel Peace Prize "for its work to draw attention to the catastrophic humanitarian consequences of any use of nuclear weapons and for its groundbreaking efforts to achieve a treaty-based prohibition of such weapons." The treaty came into force on 22 January 2021 after a fiftieth nation ratified it. Although the nuclear powers are not yet party to it, the treaty, which prohibits development, testing, possession, and use of nuclear weapons, nonetheless sets a new norm and direction for the future, much like existing treaties that prohibit the use of chemical weapons, biological weapons, land mines, and cluster bombs.

Because the "catastrophic humanitarian consequences" include not only the horrific direct effects but also potential impacts on climate and food supplies, physical scientists, including geoscientists, can offer expertise and insight into the hazards and consequences of nuclear conflict—and can be influential voices for nuclear threat reduction. In fact, at three international conferences, in 2013 and 2014 that focused on the humanitarian impacts of nuclear war, participating climate scientists helped to push authorities from nonnuclear nations to sign and ratify the 2017 treaty.

In the past, scientists have organized to exert pressure effectively on governments. Soon after physicists developed nuclear weapons in the 1940s, many then organized to warn of the dangers of nuclear arms. For example, James Franck and others published a report in June 1945 arguing against the use of a nuclear weapon in Japan; Albert Einstein led the Emergency Committee of Atomic Scientists, formed in 1946, to warn the public and mobilize scientists; and Niels Bohr urged world leaders, including Franklin Roosevelt and Winston Churchill, to preempt a postwar arms race.

The U.S. physics community has again taken steps to influence U.S. nuclear policy—and geoscientists have the chance to join and work together with this community.

Through the Cold War, many scientists worked toward arms control and cooperative security. Geophysicists developed technologies to detect underground and atmospheric nuclear tests (sensors that as a by-product, have also been used to collect Earth observations). And in the mid-1980s, American and Russian climate scientists together warned Reagan and Gorbachev of the likely effects of a nuclear winter, helping to end the nuclear arms race. Recently, the U.S. physics community has again taken steps to influence U.S. nuclear policy—and geoscientists have the chance to join and work together with this community.

Influential Voices

In 2020, the American Physical Society (APS) initiated the Physicists Coalition for Nuclear Threat Reduction with the goal of creating a national network of physical scientists to advocate for nuclear threat reduction. A supporting goal is to inform the physical science community about nuclear arms issues. In its first 2 years, the Physicists Coalition, of which we are founding members, has held more than 100 colloquia in physics departments and national laboratories around the country to introduce the community to the coalition and to provide an overview of the nuclear arms challenge. The program of colloquia is ongoing, and we continue to present webinars on specific arms control topics.

Our advocacy work includes a broad array of actions but focuses on contacts and meetings with congressional representatives and staff. Throughout 2020, the coalition, along with other groups, successfully advocated to the U.S. Congress not to approve a resumption of nuclear testing, which had been suggested by some legislators, and for the

White House to extend the New START Treaty, which limits the number of strategic nuclear weapons deployed by the United States and Russia. Soon after assuming the U.S. presidency, Joe Biden agreed with Russian president Vladimir Putin to extend the treaty for 5 years. Now the coalition's focus is on advocating for the United States to adopt a no-first-use policy, meaning that its nuclear arsenal would remain only as a deterrent to attack. Pulling the option of first use by the United States off the table can reduce geopolitical tensions that could lead to war.

The Physicists Coalition for Nuclear Threat Reduction welcomes all physical scientists, including those working in engineering science, to join, and we encourage you to host a colloquium, funded by the coalition, at your institution. The coalition offers an opportunity to be part of a movement specifically targeted at one of humanity's most existential threats. We must solve the problem of nuclear weapons so that we have the luxury of devoting our time to solving the climate crisis.

Scientists can sign up to join the coalition and inquire about hosting a colloquium at http://physicistscoalition.org/. For more information on nuclear arms and arms reduction efforts, watch a recording of Alan Robock delivering the Stephen Schneider Lecture at AGU's Fall Meeting 2021 (bit.ly/AGU21-Schneider-Lecture).

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ARE WE ENTERING THE GOLDEN AGE OF CLIMATE MODELING?

By Mark Betancourt

Thanks to the advent of exascale computing, local climate forecasts may soon be a reality. And they're not just for scientists anymore.

sdecoret/Depositphotos

In 2021, the United Kingdom experienced an extended period of windlessness; in 2022 it was struck by a record heat wave. At the same time, there were unprecedented flooding in Germany and massive forest fires in France. Are these events part of the violent opening salvo of the anthropogenic warming we've been warned about? When and where will they happen next? Climate scientists tend to demur. We just don't know—yet.

For nearly 6 decades, climate models have confirmed what back-of-the-envelope physics already has told us: An increased concentration of greenhouse gases in the atmosphere is warming the planet. Dozens of models, produced by research institutions across the globe, have given visible shape to what lies ahead: time-lapse maps of the world turning from yellow to orange to blood red, ice caps disappearing beneath the ominous contours of temperature gradient lines.

Now, at what the Intergovernmental Panel on Climate Change (IPCC) has said is a critical moment for avoiding the worst outcomes, governments are saying, We're convinced—now what do we do?

Answering that question is where our current models fall short. They show us how the planet is warming but not how that will affect the weather in a given city, or even country. Because the climate models rely, in a sense, on averages, they can't predict the outliers—those extreme events with the most potential for destruction, and the ones we most need to prepare for. But current models can't even determine whether some places will experience more droughts or floods, whether governments should build reservoirs or levees.

Our current models can't even determine whether some places will experience more droughts or floods, whether governments should build reservoirs or levees.

"A highly nonlinear system where you have biases which are bigger than the signals you're trying to predict is really a recipe for unreliability," said Tim Palmer, a Royal Society research professor in climate physics and a senior fellow at the Oxford Martin School.

It's not that we don't have the data—we just don't have the power to process them fast enough to forecast changes before they become old news. And unlike short-term weather forecasting, longer-term climate forecasting involves incorporating many more physical processes, like the carbon cycle, cloud feedback, and biogeochemistry. "They all consume computer time," said Palmer.

That's about to change. This year saw a milestone in supercomputing when the world's first exascale computer—capable of a quintillion (10^{18}) calculations per second—came online in the United States. For the first time, scientists like Palmer have said, they're about to be able to model climate on something close to the scale on which its driving processes actually happen.

Others have questioned whether accurate local climate predictions, especially decades into the future, are even possible, no matter how much expensive computing power is thrown at them. And behind the technical challenge is a logistical one, and ultimately a political one. The legion of government and university climate labs that produce climate models don't have the resources to marshal humanity's computational apex, and climate data themselves are siloed in a global hodgepodge of grant-funded research programs.

Palmer and a growing number of others have said climate scientists need to band together and make fewer models but ones with astronomically better resolution. The effort, embodied by a project the European Union (EU) announced this year called Destination Earth, would amount to a new moon shot. It won't be easy, but it could pay off.

Another Earth

The Destination Earth initiative, nicknamed DestinE (bit.ly/Destination-Earth), was launched in March 2022 as part of the EU's European Green Deal to become climate neutral by 2050. Proponents have said its potential spans to every corner of climate mitigation, from flood prevention to protecting water supplies to maintaining food production. The idea is to consolidate high-resolution models into a digital twin of Earth.

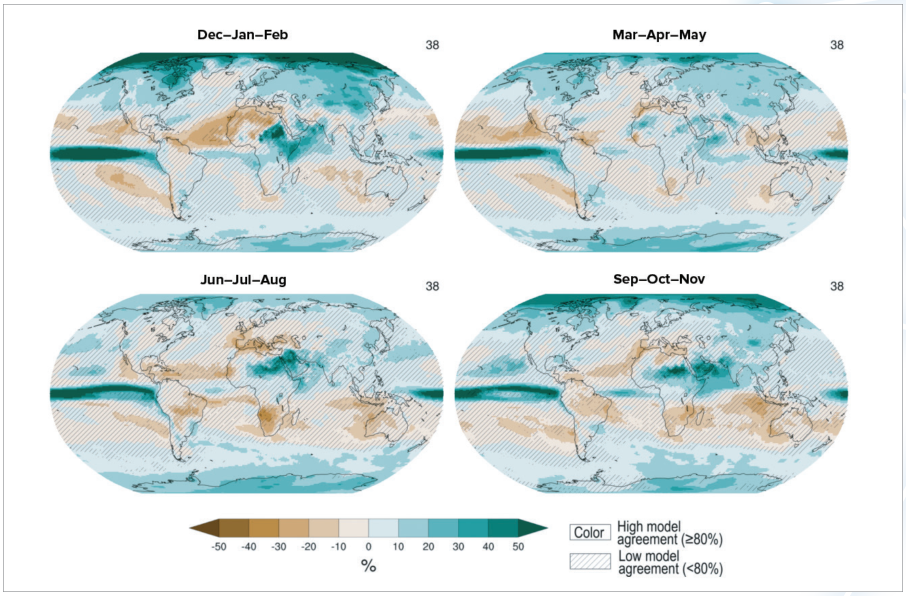
The concept of a digital twin, developed by the manufacturing industry to test and improve products more efficiently, describes a virtual replica of a physical object. Tesla, for example, builds digital twins of each of its cars based on a constant flow of sensor data, then uses analysis of the twin to continually update the real car's software and optimize performance. Earth is a vastly more complex object, with too many interrelated systems ever to be fully accounted for in a digital twin. But DestinE will attempt to use a virtual Earth in much the same way, to forecast both how the climate will change and how our attempts to weather that change will hold up, in effect creating a virtual test lab for climate policy.

DestinE will ultimately involve several sets of twins, each focusing on a different aspect of Earth. The first two, which officials ambitiously expect to be ready in 2024, will focus on extreme natural events and climate change adaptation. Others, including those focusing on oceans and biodiversity, are planned for subsequent years. The twin concept will make it easier for nonexperts to make use of the data, according to Johannes Bahrke, a European Commission spokesperson. "The innovation of DestinE lies...in the way it enables interaction and knowledge generation tailored to the level of expertise of the users and their specific interests," Bahrke wrote in an email.

The initiative is a collaboration between the European Centre for Medium-Range Weather Forecasts

(ECMWF), which will handle building the digital twins themselves, and two other agencies: The European Space Agency (ESA) will build a platform that will allow stakeholders and researchers around the world to easily access the data the initiative produces, and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) will establish a "data lake" consolidating all of Europe's climate data for use in the models.

The goal is to blend climate models and other types of data, including on human migration, agriculture, and supply chains, into one "full" digital replica of the planet by 2030. According to Bahrke, the initiative also plans to use artificial intelligence to "provide means to fully exploit the vast amounts of data collected and simulated over decades and understand the complex interactions of processes between Earth system and human space."



Exascale computing could help clarify projected long-term relative changes in seasonal mean precipitation (2081–2100 relative to the 1995–2014 base period). Diagonal lines indicate regions with low model agreement, where less than 80% of models agree on the sign of the change. Source: IPCC (2021), Figure 8.14

It's an ambitious goal, but at its core is what some have said will be a step change in how we see Earth systems. The key to its potential? Resolution.

Downscaling Models, Upscaling Physics

Climate models divide the globe into cells, like pixels on a computer screen. Each cell is loaded with equations that describe, say, the influx of energy from the Sun's radiation, or how wind ferries energy and moisture from one place to another. In most current models, those cells can be 100 square kilometers or larger. That means the average thunderstorm, for example, in all its complexity and dynamism, is often represented by one homogenous square of data. Not only are storms the often-unexpected source of a flood or tornado, but also they play a crucial role in moving energy around the atmosphere, and therefore in the trajectory of the climate—they help determine what happens next.

But it's no mystery how mountains force air upward, driving the vertical transfer of heat, or how eddies transport heat into the Southern Ocean, or how stresses in ice sheets affect how they tear apart. "We have equations for them, we have laws. But we've been sort of forbidden to use that understanding by the limits of computation," said Bjorn Stevens, managing director of the Max Planck Institute for Meteorology in Hamburg, Germany, and a close colleague of Palmer's. "People are so used to doing things the old way, sometimes I think they forget how far away some of the basic processes in our existing models are from our physical understanding."

In any climate model, smaller-scale features are parameterized, which means they're represented by statistical analysis rather than modeled by tracking the outcome of physical processes. In other words, the gaps in the models are filled through correlation rather than causation.

"We're often studying the impact of our approximations rather than the consequences of our physical understanding," said Stevens. "And that, [to me] as a scientist, is very frustrating."

Exascale computers will be able to run models with a much higher resolution—with cells as small as 1 square kilometer—allowing them to directly model more physical processes that happen on finer scales. These include many of the vertical heat exchanges that drive so much atmospheric activity, making the new models what Stevens has called "fully, physically three dimensional." The added processing power also will allow massively complex systems to be better coupled with each other. The movement of ocean currents, for example, can be plugged into atmospheric air currents and the variegated radiative and deflective properties of land features with more precision.

"We're often studying the impact of our approximations rather than the consequences of our physical understanding. And that, [to me] as a scientist, is very frustrating."

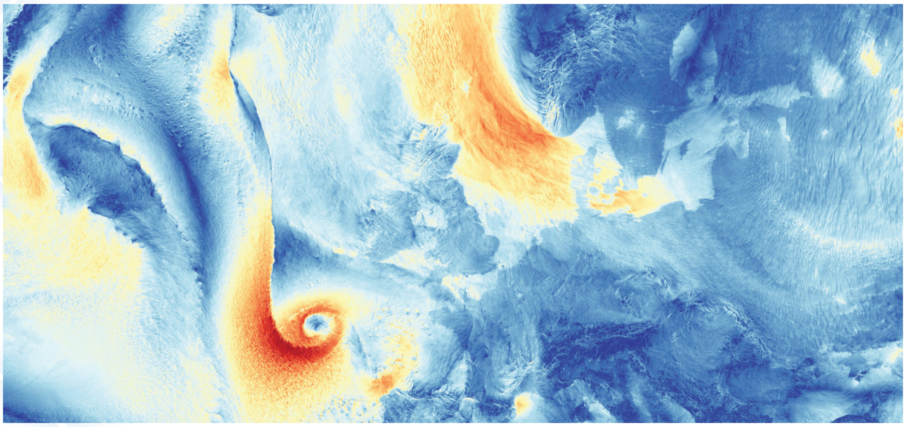
"We can implement that and capture so much more of how [such interaction] steers the climate," said Stevens. "If you finally can get the pattern of atmospheric deep convection over the warm tropical seas to behave physically, will that allow you to understand more deeply how that then shapes large-scale waves in the atmosphere, guides the winds, and influences things like extratropical storms?"

Stevens said the prospect has reinvigorated the climate modeling field, which he thinks has lost some of its vim in recent years. "This ability to upscale the physics is what's really exciting," he said. "It allows you to take physics that we understand on a small scale and look at its large-scale effect."

Laying the Groundwork

In late June 2022, more than 80 climate scientists and programmers gathered in a rented coworking space in Vienna, huddled in bunches around their laptops for a climate hackathon. The NextGEMS (Next Generation Earth Modelling Systems) project, funded by the EU's Horizon 2020 program, had just completed a 4-month run of its latest model. At 5-kilometer resolution, the run yielded two simulated years of the global climate, and the hackers were hungrily digging into the output, looking for bugs.

"We're happy when we find bugs. It's easier to find them if more people look at [the model] from very different perspectives," said Theresa Mieslinger, a cloud researcher and organizer of NextGEMS' hackathons (the inaugural one took place in October 2021). Each NextGEMS event is a chance for climate modelers to work together preparing two models, the German-developed Icosahedral Nonhydrostatic Weather and Climate Model (ICON) and ECMWF's Integrated Forecasting System (IFS), often referred to as the "European model" for weather prediction, for use in high-resolution modeling efforts like Destination Earth.



The DestinE initiative may run climate simulations at a scale of 1 square kilometer, similar to this atmospheric simulation of Great Britain and the North Sea. Shown are surface winds with increasing wind speed from dark blue to dark red. Land features are depicted only through their effect on the surface wind. Credit: Simulation by Daniel Klocke (MPI-M), visualization by Tobias Kölling (MPI-M)

Finding bugs in the models is a natural result of running them at higher resolution, not unlike taking the training wheels off your bike only to find you're not as good at balancing as you'd thought. Things are further complicated by the new ability to couple systems. A recent example: NextGEMS had connected the atmosphere to the ocean in a way that extracted too much energy from the ocean. "Suddenly models which behaved tamely at coarse resolution developed winds blowing in the wrong direction," said Stevens, who serves as a guiding presence at the hackathons. He was far from disappointed by the error. "It can feel like riding a bronco rather than a merry-go-round pony, which is scientifically exhilarating."

Part of the hackathons' goal is to train modelers in handling the sheer volume of data involved in high-resolution modeling. Even at a resolution of 5 kilometers, the output of NextGEMS' latest run is about 1 terabyte per simulated day, and a model should be run many times to average out noise.

Knowing how to handle the data is one challenge. Receiving them from the supercomputer is another. DestinE's fix for that transmission challenge will likely be to publicly stream the data from high-resolution models as they run, rather than having to store them on disk. Anyone could design applications to identify only the data they need to answer a specific question. Stevens likened this to fieldwork in which researchers place instruments out in the world to make observations. In this case, the instruments (apps) would be observing aspects of the world's digital twin as it spins through its kaleidoscopic changes in fast motion.

Making the data public would also prevent users from having to seek help with a model run tailored to their needs. "I really like this idea that it's not an individual thing, which often depends on some connections that one person has to another or a group of scientists," Mieslinger said. "Streaming democratizes data access. It allows everyone on our globe to access the information that climate decisions are based on."

Applied Physics

Among the NextGEMS hackathon's attendees were representatives from the clean energy industry, just one of many that need climate data: Without detailed information about how reliable clean energy sources are, and how susceptible they are to damage from extreme weather, the industry will struggle to establish a stable electrical grid.

The evidence of that is already plain; in 2021 the United Kingdom experienced its lowest average wind speeds in 60 years. That was bad news for the country's wind farms—wind power is generated as the cube of wind speed, so even a 10% reduction in wind speed means nearly 30% less power. Windlessness was also bad news for the four nearby countries (Belgium, Denmark, Germany, and the Netherlands) that recently had pledged to increase wind generation capacity in the North Sea tenfold by 2050. No one saw the doldrums coming.

"Before the wind drought, the kind of question I was being asked was, 'Where's the windiest place around Europe to put these wind turbines?'" said Hannah Bloomfield, a climate risk analyst based at the University of Bristol. "But then the question kind of changed

Attendees at the NextGEMS hackathon in July 2022 pore over data from a recent run of the project's high-resolution model. Credit: Yuting Wu

a bit after we had a wind drought." Wind farmers started asking where there was wind even during the drought. It was as if they were realizing in real time that change is the new normal.

Bloomfield said she had trouble answering the wind farmers' questions without higher-resolution models. "You see a lot of studies where they want to represent activity at an individual wind farm or a power plant, but they're having to use, say, 60- to 100-kilometer grid boxes of climate data to do it." The vertical resolution of the new exascale versions could be especially key in this instance: Current models can't directly solve for wind speed extremes at the height of most wind turbine rotor hubs, around 100 meters.

Palmer said the new models also could help determine the root causes of regional changes in wind, and so better predict them. The phenomenon called global stilling, for example, is a result of the Arctic surface warming faster than the middle latitudes. The discrepancy reduces the temperature gradient between the regions and slows the wind that results as the atmosphere tries to balance things out. But the upper atmosphere in the Arctic isn't warming as fast as the surface; the winds in Europe could have died down for another reason. Palmer believes the new models are poised to reveal an answer.

Bloomfield also works with insurance companies that are trying to improve the accuracy of their risk assessments. For example, sharper models could help them price premiums more appropriately by making it clear who lives in a flood-prone area and who doesn't. "If you've got a low-resolution model, it might make [the flood-prone region] look like a bigger area than it is," she said, "or it might just miss the flood entirely."

Researchers like Bloomfield are the sinews connecting industry stakeholders, policymakers, and the complex science of climate modeling. But as climate becomes part of nearly every decision made on the planet, they can't continue to be. Bloomfield, who is part of a group called Next Generation Challenges in Energy-Climate Modelling, recognized the importance of both educating stakeholders and making climate modeling data more accessible to everyone who needs to use them.

"This stuff is big, right? It's chunky data. Although you can now produce [them] with this exascale computing, whether industries have caught up in terms of their capabilities to use [them] might be an important factor for projects like [Destination Earth] to think about," Bloomfield said.

"If you've got a low-resolution model, it might make [the flood-prone region] look like a bigger area than it is, or it might just miss the flood entirely."

Delivering on the Promise

Stevens agreed that university labs can't continue to carry the responsibility of lighting the way forward through climate change. "It's ironic, right? What many people think is the most pressing problem in the long term for humanity, we handle with a collection of loosely coordinated research projects," he said. "You don't apply for a research grant to say, 'Can I provide information to the farmers?'"

Stevens has argued that the world's decisionmakers need to rely on climate models the same way farmers rely on weather reports, but that shift will require a concerted—and expensive—effort to create a kind of shared climate modeling infrastructure. He and Palmer proposed that the handful of nations with the capacity to do so should each build a central modeling agency—more farsighted versions of ECMWF in Europe or the National Weather Service in the United States—and actively work together to supply the world with reliable models that cover its range of policy needs.

"If the world invested a billion dollars a year, maybe split between five or six countries, this could revolutionize our capabilities in climate modeling," said Palmer.

But some in the climate science community question whether higher-resolution models can really provide the information policymakers are looking for. Gavin Schmidt, director of the NASA Goddard Institute for Space Studies (GISS) and principal investigator of the GISS coupled ocean-atmosphere climate model, ModelE, said there may well be a ceiling to what we can predict about long-term variability in an ultimately chaotic climate system. One example, he said, is local rainfall 30 years from now, which can depend on the chaotic behavior of the circulation even in current models. "These trends are probably not predictable, and that won't change with higher resolution."

"From a scientific-technological perspective, climate is still treated as an academic hobby."

Schmidt pointed out that higher-resolution models can't be run as often, making it harder to average out noise through a robust ensemble of repetitions. "Resolution is very, very expensive. With the same computational cost of one 1-kilometer climate model, you could be running tens of thousands to hundreds of thousands of lower-resolution models and really exploring the uncertainty."

There just isn't enough evidence that kilometer-scale models will produce different answers than existing models do, he said. "As a research project, I think these are great things to be doing. My biggest concern is that people are overpromising what's going to come out of these things."

A New Moon Shot?

NextGEMS is now trying out its model with a coupled ocean and atmosphere, running at a resolution of 2.5 kilometers for only a few months. Japanese researchers are working on models that resolve at only a few hundred meters globally, which Mieslinger gleefully called "absolutely crazy." So far, none of this is being done on an exascale computer but, rather, on the petascale computers—less than half as fast—that are currently operational in Europe and Japan.

Atmosphere-focused climate models are now being run at 3-kilometer resolution on Frontier, the world's first exascale computer, at the Oak Ridge National Laboratory in Tennessee. The U.S. Department of Energy (DOE) has been developing a program similar to DestinE for the past 10 years, preparing to have its Climate and Earth System model ready for this moment. The project, known as E3SM, for Energy Exascale Earth System Model, is specifically geared toward questions of importance to DOE, like how the production of bioenergy will affect land use, and in turn affect the climate system.

Frontier is expected to be able to produce a simulated year of 3-kilometer climate model data in less than a day. But even E3SM will need to share time on Frontier with DOE's other heavy-lift applications, including those simulating nuclear explosions. Such national security needs have traditionally taken priority, but governments are tracking and predicting the results of climate change as matters of national security.

In June 2022, Europe announced plans for its first exascale computer, JUPITER (Joint Undertaking Pioneer for Innovative and Transformative Exascale Research), to be shared among the continent's many data-heavy applications. But Stevens said it will be difficult to provide reliable high-resolution climate data on an ongoing basis without exascale computers that are dedicated to the task full time and a centralized organization leading the way. He hopefully cited other cost-intensive human achievements—the CERN (European Organization for Nuclear Research) Large Hadron Collider, the James Webb Space Telescope—as precedents. And, he pointed out, governments have stepped up before. "NASA was created when we recognized the importance of space. The Department of Energy or similar institutions in other countries [were prioritized] to tame the atom," he said. On the other hand, "from a scientific-technological perspective, climate is still treated as an academic hobby."

Even if higher-resolution models can yield the climate answers we need, whether the world's governments will choose to muster the collective resolve exemplified by the Space Race remains to be seen. Reminders of geopolitical barriers are everywhere—Palmer can't apply for DestinE funding because the United Kingdom has left the European Union ("Brexit's a nuisance," he said (see bit.ly/Eos-European-funding-impasse)), and the conflict in Ukraine has diverted attention from reducing our consumption of fossil fuel in the future to worrying about where we can get enough of it now. But, Palmer countered, the conflict has also made clear how much easier things would be if we didn't need fossil fuels at all, and the urgency of getting serious about a stable clean energy grid.

That means high-resolution models, or at least the chance to see what they can do, can't come soon enough.

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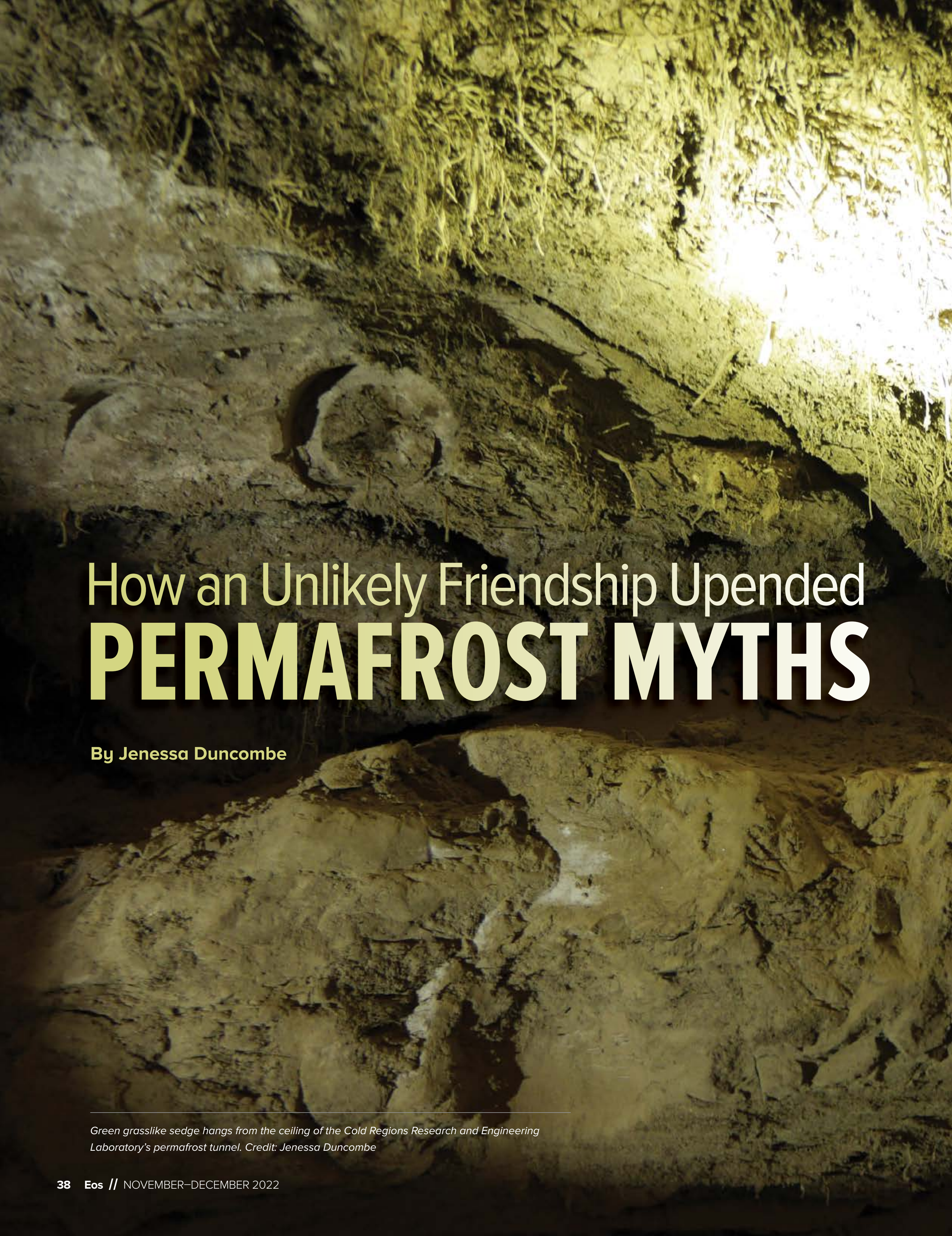
▶ Read the article at bit.ly/Eos-climate-modeling-golden-age



How an Unlikely Friendship Upended PERMAFROST MYTHS

By Jenessa Duncombe

Green grasslike sedge hangs from the ceiling of the Cold Regions Research and Engineering Laboratory's permafrost tunnel. Credit: Jenessa Duncombe

“Beautifully long arguments” between an American scientist and a Russian researcher helped clarify fundamental assumptions about permafrost thaw.

The Curve

The Curve is a series charting the mysterious rise of methane in our atmosphere and the quest to find its source.

On a clear, subzero day in Fairbanks, Alaska, I followed researchers Taylor D. Sullivan and Daniel Vandevort to a cold, dusty, underground tunnel.

They fitted hard hats over stocking caps and led me through a corrugated metal tube to the earthen tunnel. Sullivan clicked on his flashlight and panned over walls of terra-cotta-colored dirt. We were standing inside an airy passageway of permafrost, extending a length of more than five football fields into the side of a hill.

The smell of moldy cheese in a barnyard wafted over us. It smelled of "bison bits and mammoth bits," said Sullivan, a geophysicist with the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, which owns the tunnel. Vandevort, a civil engineer with the laboratory, said the smell could stick to you for days.

It was March 2022, and I'd gone to Alaska to learn about a wild card of climate change—the vicious feedback loop of warming and Arctic thaw. Many people study permafrost thaw, but few visit the Arctic in the winter. In particular, I was there to learn more about an enduring mystery of permafrost thaw: why winter methane emissions are as high as they are.

It's not just the Arctic: Worldwide, methane emissions have been rising at an accelerating rate since 2007, and scientists aren't sure why. Last year, about 640 million metric tons of methane entered the atmosphere, and global concentrations hit their highest value recorded since data collection began in 1983.

Although scientists believe that Arctic methane contributes only a tiny fraction of today's rise in emissions, they worry that will change. Greenhouse gas emissions from the thawing permafrost could use up 25%–40% of the allowable emissions to keep the global average temperature increase below 2°C, according to Susan Natali at the Woodwell Climate Research Center in Falmouth, Mass.

Roughly 30 years ago, the notion that permafrost could release so much methane was not a significant consideration. But in the 1990s a grounbreaking discovery by a Russian scientist and an American researcher investigating winter methane emissions revealed a source of methane that was previously unaccounted for. In the years following, estimates of climate warming from permafrost would more than double.

(Left to right) Terry Chapin, Sergey Zimov, and Sergey Davidov search a map for likely places of permafrost thaw at the Northeast Science Station in Siberia in 1996. The skull of an ice age bison rests on the table. Credit: Terry Chapin

A New Collaboration

There wasn't a lot of interaction between Russian and American scientists at the time, a divide that has deepened with the current conflict in Ukraine. The language barrier kept Russians out of top-tier Western publications, and the country was fresh off the fall of the Soviet Union in 1991.

Terry Chapin, a faculty member at the University of California, Berkeley at the time, sought to change that for more than merely academic reasons. His wife, Mini, had studied Russian in college. "It was a chance for Mini and me to do science together," said Chapin.

In 1991, Chapin met Siberian scientist Sergey Zimov at an Arctic climate change conference at Oregon State University. Zimov, a geophysicist, had traveled far. He lived at a remote northern research station in Cherskii, Russia, that he had cofounded in the 1970s with three other families. He'd been studying permafrost, tundra, lakes, and more at the station ever since.

"I was just really impressed with his brilliance," said Chapin.

Situated far from the halls of Western institutions, Zimov had some far-flung ideas. "We used to have these beautifully long arguments," said Chapin. "And in almost every case, the things that he was

THERE WASN'T A LOT OF INTERACTION BETWEEN RUSSIAN AND AMERICAN SCIENTISTS IN 1991.

The U.S. Army Corps of Engineers excavated this tunnel 50 years ago to experiment with new permafrost construction techniques, but in the process, they dug back in time and found the remains of a plethora of ice age life. Now, the tunnel is a beacon for the study of permafrost, geology, ice science, mining, and construction. Credit: Jenessa Duncombe

talking about, he eventually convinced me that he was correct."

One intriguing question Zimov posed, for example: Wasn't it odd that in global databases, atmospheric methane peaked at high latitudes during winter? None of the ideas Zimov had to address this question "fit with the conventional explanations of what causes methane to be released from the Earth's surface," said Chapin.

Over many years, Chapin and his wife visited Zimov in the Northeast Science Station in Siberia. On the third visit, he worked with Zimov on what would become a fundamental discovery.

Ice Age Buffet

Decades later and hardly a dozen steps into my walk into the permafrost tunnel, a paleolithic bison appeared. Its tusk jutted out near the ground, hidden behind electrical wires. I asked whether I could touch it, and Vandevort shrugged. "It's not a museum."

The grooves of the tusk felt smooth as a river stone. More bones protruded from the walls, and Sullivan and Vandevort explained their provenance (the last ice age) and age (between about 14,000 and 30,000 years old). These beasts had roamed the grassy plains of Alaska's interior during the Pleistocene, evading the claws of horse-sized short-faced bears and saber-toothed cats.

Sullivan and Vandevort guided me farther down the corridor hung with string lights, their heels kicking up fine dust. Sullivan stopped to brush his hands through the loose strands of grasslike sedge hanging from the tunnel's ceiling. The sedge had been dead for 31,000 years, but the cold kept it so perfectly preserved that the blades still shone green with chlorophyll.

Until Chapin and Zimov buddied up, scientists thought these ice age relics had little to do with Arctic thaw. Studies in the early 1990s in Alaska and Minnesota suggested

THE CARBON HADN'T WAFTED THROUGH OUR ATMOSPHERE SINCE THE TIME OF THE MAMMOTH.

that greenhouse gases from the frozen ground came from modern plants. It's not so far-fetched: In forests today, trees suck in carbon but eventually decay and release it back into the atmosphere.

But during his time in Cherskii, Chapin collected methane samples from lake bubbles above thawing permafrost and brought them back to the United States, where he persuaded a friend to radiocarbon date them. The carbon in the methane was 27,200 years old—it hadn't wafted through our atmosphere since the time of the mammoth.

Microbes living in the sediments of Siberian lakes were converting ice age carbon into modern-day methane emissions, wrote Zimov, Chapin, and colleagues in their landmark paper in *Science* in 1997 (bit.ly/Siberian-methane).

The bones of a mammoth nicknamed "Willy" lie in an underground permafrost tunnel near Vault Lake, Alaska. Credit: Jenessa Duncombe

Microbes Can Chill

That wasn't the only discovery the two made. Zimov dug several cores of permafrost from an eroding Siberian lakeshore. He flooded the cores with lake water and stored them at different temperatures in the lab.

Gas gathered at the top of the cores, and Zimov made a startling finding: Permafrost microbes pumped out methane even at 0°C–1°C. The microbes living in this wetland ecosystem thrived at cold temperatures.

Zimov's cores mimicked the environment of many water-bogged permafrost landscapes. In these oxygen-poor environments, ice age debris are no match for bacteria, which digest the cellulose from dead plants into acetate, hydrogen gas, and simple carbohydrates. Hungry methanogens (methane-producing microbes) slurp up these compounds and churn out methane.

A quarter century and half a world away, the earthen walls I stared at in that Fairbanks tunnel were strikingly similar to Zimov and Chapin's Siberian permafrost. The permafrost in the Cold Regions Research and Engineering Laboratory is "one of the most accessible large-scale exposures of Yedoma permafrost on Earth," according to a paper in *Frontiers in Earth Sci-*

Snow blankets the entrance of the Cold Regions Research and Engineering Laboratory's permafrost tunnel. Credit: Jenessa Duncombe

IF THAWED, EACH CUBIC CENTIMETER OF PERMAFROST IN FRONT OF ME COULD SUPPORT A BILLION MICROBES: A BILLION MICROBES JAMMED INTO THE VOLUME OF A SUGAR CUBE.

ence. Yedoma, a type of carbon-rich permafrost thick with ice, is the same type that underlies Zimov and Chapin's lakes, and it's become synonymous with scientists' collective anxiety about permafrost thaw.

If thawed, each cubic centimeter of permafrost in front of me could support a billion microbes: a billion microbes jammed into the volume of a sugar cube.

"The Chapin paper is prescient in that the winter thaw of lakes is now happening," said ecologist Ben Poulter of the NASA Goddard Space Flight Center in Greenbelt, Md., who tabulates methane sources worldwide.

The pair's graduate student, Katey Walter Anthony, would go on to prove that methane emissions from lakes could account for half of all warming from permafrost thaw, even though lakes make up only a tiny fraction of land area.

As it often goes in science, these discoveries started with a simple question about winter methane emissions, and the answer led to more questions than it solved. In the next installment of *The Curve*, we'll learn about today's research into the question of the rising amount of methane being released into our atmosphere involving state-of-the-art airborne sampling, calls to nuclear submarines, and a few angry moose.

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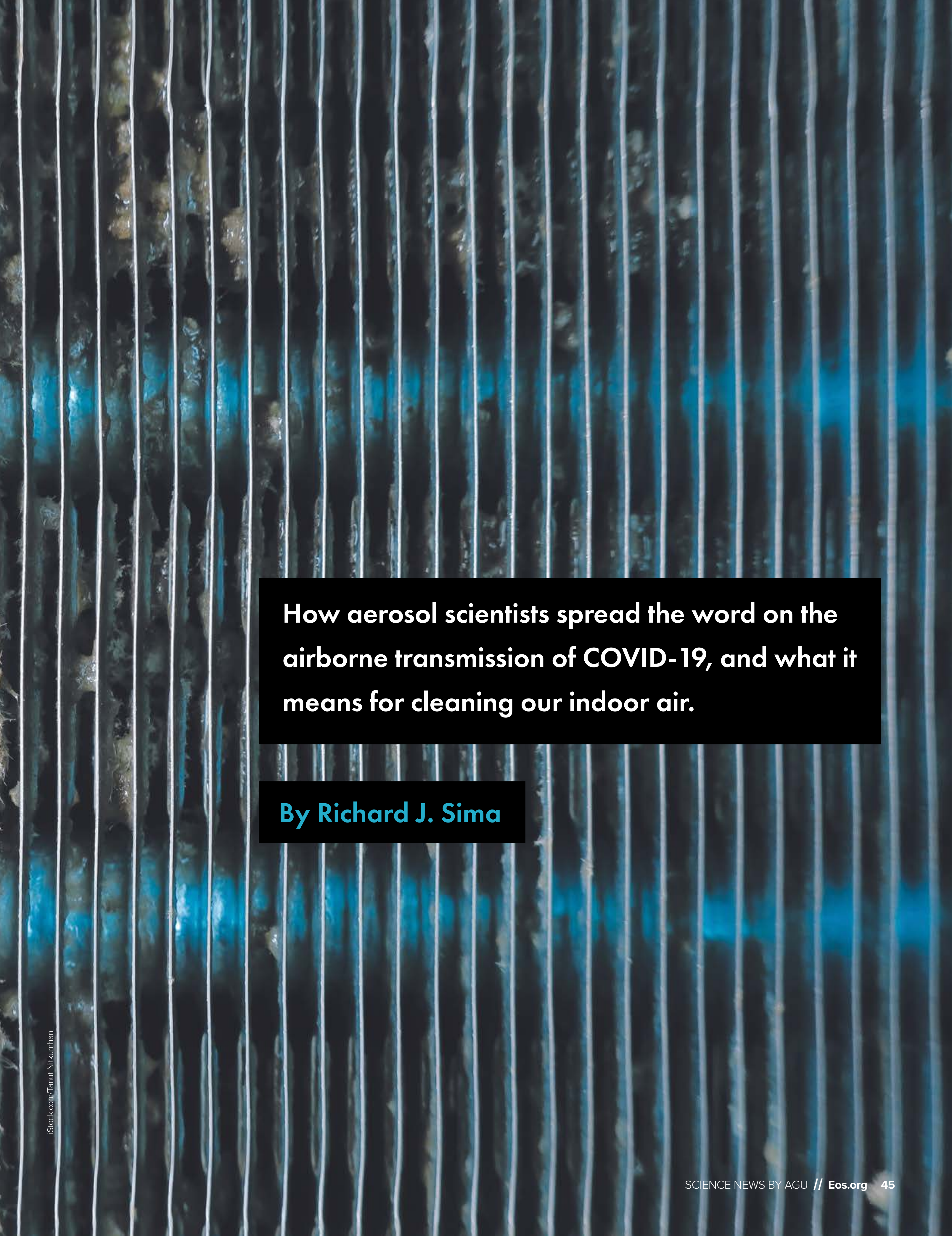
▶ **Read the article at bit.ly/Eos-permafrost-myths**

Indoor Air Pollution in the Time of Coronavirus



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How aerosol scientists spread the word on the airborne transmission of COVID-19, and what it means for cleaning our indoor air.

By Richard J. Sima

Knowing that an invisible, infectious virus may be lingering in the air of a stuffy room is an unsettling thing.

But even more unsettling is *not* knowing it could be there.

At the beginning of the COVID-19 pandemic, much of the world was unaware that the SARS-CoV-2 coronavirus could be transmitted through the air. Following public health guidance, we dutifully washed our hands and kept our distance; some of us disinfected surfaces and even our groceries.

But the coronavirus was not just transmitted through short-range droplets emitted through coughing or sneezing.

Aerosol and atmospheric scientists from around the world were the first to sound the alarm on airborne transmission of coronavirus: Fine aerosol particles carrying the virus could linger and accumulate in the air for minutes to hours. Anyone sharing the space—even if they were farther away than the social distancing standard of 2 meters (6 feet)—could be at risk for inhaling the infected air particles.

But even before we began masking and avoiding crowded spaces, bad indoor air quality was already responsible for millions of deaths and debilitating health issues. And though we spend 90% of our time indoors, there is generally a lack of appreciation and awareness of the importance of the air around us. The composition of our indoor air matters to our health, whether it contains novel coronavirus or pollutants. But unlike outdoor air, the quality of the air we breathe indoors is not regulated.

If water is contaminated, we can still purchase bottled water, said Lidia Morawska, a physicist at Queensland University of Technology in Australia who runs an air quality lab specializing in airborne particulate matter. "But we have absolutely no choice on air we breathe. And we breathe continuously: If we stop breathing for 3 minutes, we'll die. That's the importance of indoor air quality," she said.

Heightening interest in indoor air quality could save millions of lives—and prepare us for the next airborne pandemic.

The revelation that COVID-19 can spread through the air could provide the attention and momentum needed to clear our indoor air for good. Some countries, such as Taiwan, already have regulations addressing indoor air quality. Others, such as Finland, are pursuing a holistic strategy involving health care and educational outreach as well as standards for managing air quality in indoor environments. In March 2022, the Biden administration launched the Clean Air in Buildings Challenge, calling on building owners and operators to adopt key strategies for improving indoor air quality as part of a broader strategy for reducing the spread of COVID-19.

Heightening interest in indoor air quality could save millions of lives—and prepare us for the next airborne pandemic.

"You know, it's really too bad [awareness] took so long to get here," said Linsey Marr, an expert on airborne transmission of viruses at Virginia Polytechnic Institute and State University. "But at the same time…I thought it would take a generation— I thought it would take 30 years for us to come this far if there had not been a pandemic."

Aerosol Scientists Sound the Alarm

At the beginning of the pandemic in 2020, most public health agencies, including the World Health Organization (WHO), did not recognize airborne transmission—aerosol particles laden with infectious agents that can travel over long distances and for a long time through the air—as a viable route for spreading COVID-19. Instead, the focus was on mitigating risk from large respiratory droplets that, expelled by coughs or sneezes, would fall quickly to the ground, leading to recommendations for handwashing and physical distancing.

But for many aerosol and atmospheric scientists, airborne transmission was not only a possibility but also the most likely explanation for the pattern of spread.

Superspreader events, such as the rehearsal of the Skagit Valley Chorale outside of Seattle, showed infections that could not be explained by close contact alone. In the Skagit Valley Chorale incident, between 32 and 52 people contracted COVID-19 following a rehearsal attended by 61 people. Two died. Another well-documented case of COVID-19 spreading over long distances, through a poorly ventilated restaurant in Guangzhou, China, even included video recordings showing no close contact between infected people.

In addition, poorly ventilated indoor spaces, such as prisons and nursing homes, seemed to experience the worst outbreaks, whereas the likelihood of COVID-19 transmission was far lower outdoors than in.

"It was like, 'Why, of course, it's so obvious that it's airborne,'" said Shelly Miller, an air pollution specialist and environmental engineer at the University of Colorado Boulder. "We were just flabbergasted that this was not something to be considered seriously."

In the decades before COVID-19, researchers had demonstrated that viruses could be released, spread, and linger in aerosols for far longer and farther than was considered by health officials. "I think it was obvious to me and my colleagues because we understand the physics of airborne particles," said Miller, lead author of the Skagit Valley Chorale study. "The particles don't care what organism" they are—be it a fungus, bacterium, or novel coronavirus.

Before the pandemic, for example, Morawska carried around her own carbon dioxide meter to keep informed about the quality of the air surrounding her. "It's so small it fits into any handbag I have," she said. If someone was sick at a family gathering or in a staff meeting, she could ensure they were in a well-ventilated area and positioned where their exhaled air would not flow toward others. She would also mask up when she herself was ill.

"In reality, we knew that respiratory viruses such as SARS-CoV-2 spread through the air because they're emitted from our respiratory activities—mouth, nose—when we speak, when we breathe, when we do anything else," said Morawska, who has been an adviser on air quality to WHO since 1990. "There was really no disagreement, no question marks amongst scientists about this before the pandemic."

However, finding direct evidence linking infected aerosols to disease spread is difficult, said Yuguo Li, a researcher of building environments at the University of Hong Kong and editor in chief of the journal *Indoor Air*.

Linsey Marr of Virginia Polytechnic Institute and State University is an expert on airborne transmission of viruses. Credit: Virginia Tech

For direct evidence, you would need to prove at least three things, said Li, who is part of the Lancet COVID-19 Commission. First, you need to show that someone infected breathed out aerosols. Second, you need to show that the aerosols in the space had sufficient viable virus in them. And third, you need to show that someone inhaled them and got infected. Even if all the mechanistic steps of transmission make sense, they are each difficult to prove.

"It's difficult to get direct evidence [for airborne transmission] every time after this occurs," Li said. "You cannot trace back the wind in your backyard 100 years ago."

But there was still enough evidence to follow the precautionary principle for preventive action in the face of uncertainty. Li wondered, Are we going to wait around for definitive evidence when we know enough to take reasonable actions?

Throwing Caution to the Wind

In early March 2020, the director-general of WHO announced to the world that the coronavirus is not airborne. The organization had convened a committee to figure out how the virus is transmitted and how to prevent it, said Jose-Luis Jimenez, a chemist and aerosol expert at the University of Colorado Boulder, noting that the committee had six experts on handwashing and zero on airborne transmission. At the end of March 2020, the WHO tweeted "FACT: #COVID19 is NOT airborne."

For Morawska, this was a turning point and a realization that something had to be done.

Over the course of 3 days—"I realized time is a factor"—Morawska brought together a group of 36 scientists who signed a petition with the aim of convincing health authorities that the current scientific understanding was different from what WHO was saying.

"Experts were in agreement," Morawska said, "that this virus, like any other respiratory virus, spreads through the air. It was the disagreement between public health authorities, who were basically spreading misinformation, and experts from many different areas, [who] were trying to correct this."

The letter initially led to conversations with WHO but no further action.

"They yell at us, basically. They think we're like the 5G [conspiracy] people," said Jimenez, who was part of the group of 36. "They still meet with us, but they don't take us seriously."

The letter, signed by 239 aerosol and atmospheric scientists, was published in July 2020. Shortly after, WHO held a press conference acknowledging airborne transmission as a possibility, albeit with disclaimers that such spread is relatively rare.

"But the significance of this was that 3 months were lost, a critical 3 months, which means that public health

At the end of March 2020, the WHO tweeted "FACT: #COVID19 is NOT airborne."

Lidia Morawska runs an air quality lab specializing in airborne particulate matter

authorities around the world didn't do anything about their own transmission," Morawska said.

Further, the letter was not widely accepted by the medical community, Marr said, likely because there weren't many medical doctors who signed it. There are only a few experts in the world who study both viruses and air.

But consensus continued to slowly build, and scientific evidence for COVID-19 airborne transmission has only grown. Following a National Academy of Sciences workshop in August 2020, Marr, along with Kim Prather and Jimenez, published an article in *Science* saying that SARS-CoV-2 is airborne. Afterward, the Centers for Disease Control and Prevention (CDC) started changing its tune about the possibility of airborne transmission, Marr said.

It was only in the spring of 2021 that airborne transmission of coronavirus became more widely accepted when three major medical journals—the *Lancet*, the *BMJ*, and the *Journal of the American Medical Association*—published articles about its importance and the accumulating evidence.

When asked for comment, a spokesperson for WHO wrote in an email in late April 2022 that "the terms used to describe transmission of SARS-CoV-2 have differed across scientific disciplines over the course of the pandemic. WHO has been communicating about the risk of all modes of transmission of SARS-CoV-2 including aerosols since the early stages of the pandemic. Our scientific understanding of SARS-CoV-2 continues to evolve. The emergence of SARS-CoV-2 Variants of Concern with increased transmissibility and greater binding affinity to the host entry receptor, ACE2, highlights the need to reiterate the risk of transmission of SARS-CoV-2, including airborne transmission at both short- and long-ranges, depending on the settings."

"The consensus of COVID aerosol transmission comes out in a very sad manner, with more and more people dying," Li said. "This is an unfortunate, natural experiment with our life."

Communicating the Latest Science

Because it was difficult for scientists to publish their results, Twitter became a way to reach people and learn what evidence was missing.

Jimenez became glued to Twitter starting in March 2020. There, he shared information, built a community of scientists, and debated skeptics. "I probably spent a third of my working time on that," Jimenez said. By the time he took a break in July 2021, he was "exhausted." But then the Omicron variant hit, and he returned to high-intensity engagement.

He was also able to make the latest COVID-19 information more accessible, tweeting in both English and Spanish, a language that had fewer experts available to communicate crucial information.

"In some respects, it seems that the public got to this answer quicker than parts of the infection control community [did]," said William Nazaroff, an air quality engineer at the University of California, Berkeley and former editor in chief of *Indoor Air*. "It wasn't that hard to persuade people that this really is airborne. You could use a mask, stay away from overly crowded, poorly ventilated conditions, and the public got that faster than some parts of the scientific community [did]."

Overturning Public Health Dogma

Part of the reason it was so hard and took so long for COVID-19 to be accepted as airborne by the medical community was a "default assumption" that diseases generally did not travel through the air, Marr said.

"It's in textbooks that these types of diseases are spread by large droplets that spray onto someone's eyes, nostrils, or lips, and it was just kind of accepted… without thinking about the mechanisms or the fundamental science behind that," said Marr.

This long-standing dogma is a problem of history, Jimenez said—ancient history. The Greek physician Hippocrates believed that dirty air—miasma—was the root of illness, a view that persisted for more than 2 millennia. In 1910, influential epidemiologist Charles Chapin, with the aid of germ theory, popularized the idea that infection came from contact or droplet transmission. Since then, droplet transmission has become the dominant view.

Before the pandemic, only a handful of respiratory illnesses—tuberculosis, measles, and chicken pox—were accepted as having airborne transmission.

"There was so much resistance to the idea that flus and colds even are airborne," said Marr, who coauthored a review of other respiratory viruses that could be transmitted through the air and whose research focused on flu transmission before the pandemic. But in addition to rethinking COVID-19 transmission, "I think that's turning now, too, maybe."

“We’ve had a bit of a pendulum swing,” agreed Nazaroff.

“The state of understanding and what we learned through experience with COVID is in some ways surprising,” explained Nazaroff, who has done research on the airborne spread of treatment-resistant tuberculosis. “It almost seems self-evident that a respiratory infection…is emitted from somebody who is infectious and then inhaled by a susceptible person as the primary mode of transmission.”

Every time we talk, cough, sneeze, or breathe, we emit particles of respiratory secretions and saliva in a wide range of sizes, from less than a micrometer in diameter to more than a hundred. If there are pathogens in our respiratory system, they could hitch a ride on these particles and be transmitted.

Larger particles, responding readily to gravity, fall quickly to the ground close to the source, within about 2 meters. Smaller particles (aerosols) can remain aloft for minutes to hours, buoyed by air currents, before eventually falling to the ground if the air remains motionless. These aerosols are responsible for airborne transmission and can occur at short range (within 2 meters), where they are most easily transmitted because of higher concentrations of pathogen-containing particles; at long ranges (within a shared room); or even at longer ranges (even in different buildings).

It has been difficult to dislodge public health conceptions of which respiratory particles could be aerosolized. Medical textbooks, for example, considered any droplet larger than 5 micrometers to be one that will fall to the ground quickly, Marr said. But that number was the result of a 60-year-old scientific misunderstanding that, like a virus, propagated until it was established as medical dogma. The research evidence has shown that much larger particles (50–100 micrometers) can remain airborne, particularly if there are ambient air currents, and can be carried more than 2 meters. Though there is no definitive cutoff for how large a particle needs to be to be considered a droplet, the threshold is closer to 100 micrometers, and many factors (such as how quickly it was expelled and the speed, temperature, and humidity of the surrounding airflow) can affect its ability to remain suspended.

Another hurdle was that the public health community had “a different way of gaining an understanding of a complex process,” Nazaroff said. For them, the gold standard is a randomized controlled trial that compares randomly assigned participants receiving an intervention with another group without it, “whereas from a physical science perspective, if I can show A goes to B goes to C goes to D goes to E goes to F—then I can connect A and F and I’m persuaded.”

Approaches from public health and different research disciplines have value, scientists said. “I hope the pandemic has brought more attention to this and to the importance of interdisciplinary and multidisciplinary collaborations to understand this,” said Marr.

Health officials also may have been reluctant to declare COVID-19 as airborne because it would shift responsibility from the individual, Morawska said. If COVID-19 were transmitted only through droplets or close contact, health was in the realm of individual responsibility: If you got sick, it was because you did not get vaccinated, wash your hands properly, or wear a mask. But if the virus could linger and spread in the air we all breathe, then the government and public health agencies needed to do something more systematic and costly.

Finally, in December 2021, without announcement or fanfare, WHO quietly changed its website guidelines to acknowledge that COVID-19 could be spread by airborne transmission, marking the first time the public health organization described the coronavirus as “airborne” and a reversal of its firm declaration to the contrary at the start of the pandemic.

“Science is a complex, messy business at the frontier,” Nazaroff said. “It’s a human endeavor, so there are people’s egos and ambitions at stake. In a way it’s too bad, but it’s also not surprising. We’re all human actors as scientists, and we bring our strengths and our weaknesses to the enterprise.”

Jimenez gave a different perspective on the WHO’s response: “This is one of the biggest errors in the history of public health. They don’t want to admit it.”

Indoor Air Quality Is Essential

The pandemic has brought into sharp focus the importance of the air indoors, where most of us spend most of our lives. Indoor air quality problems were all around us before the pandemic and will linger long after if we do nothing about them.

“When you look at how many contaminants are in the average house in the U.S. and Europe, it’s comparable to Mexico City outdoors on a really bad day,” said Jimenez.

Close to 4 million people worldwide are estimated to die prematurely each year because of the health effects of indoor air pollution. Poor air quality indoors is linked to a litany of health issues, including allergies, asthma, lung diseases, and cardiovascular diseases. It is also linked to absenteeism and poorer cognitive performance.

Our indoor air is not just a reflection of outdoor air getting in. Although pollution from the great outdoors can enter buildings, most of the pollutants arise from within. We may regularly produce combustion by-products like carbon monoxide, particulate matter, and smoke from our heating or cooking sources. In addition, personal care and cleaning products release all sorts of organic compounds; some building and furniture materials release formaldehyde.

There are natural pollutants as well, such as radon (a carcinogen), mold, pet dander, and dust. And as COVID-19 has taught us, aerosols in the air can also carry infectious agents.

Climate change, as usual, may make things worse. Worse and longer allergy seasons and worsening wildfires increase the amount of pollen, smoke, and soot making their way indoors. Carbon dioxide, which we release with every exhalation, accumulates indoors at levels found to be harmful to cognition.

> **“The consensus of COVID aerosol transmission comes out in a very sad manner, with more and more people dying. This is an unfortunate, natural experiment with our life.”**

Fortunately, we already have the know-how to dramatically improve indoor air quality.

Technological advances like more sensitive tests to detect virus loads in respiratory fluid allowed aerosol scientists to make measurements they couldn't do routinely just 2 decades ago, Nazaroff said. Having said that, "I don't think there's any new, amazing technology that's just gonna zap the pathogens out," said Marr. "I think we can get a huge amount of benefit by better implementing the basic things we know about ventilation and filtration."

Improving ventilation in a building can be as simple as opening a window, which increases airflow and dilutes any viruses or pollutants. Air filters and air cleaners can be effective at reducing the amount of contaminant in the air.

For pathogens, including coronavirus, ultraviolet (UV) light treatment is an effective disinfectant, Morawska said. "There's a lot of discussion about this aspect now because this technology has been known for a long time, for over 80 years. And it's been used effectively in many places, particularly in health care."

In an editorial for *Indoor Air*, Nazaroff articulated four principles expressed in 12 words for achieving good indoor air: Minimize indoor emissions. Keep it dry. Ventilate well. Protect against outdoor pollution.

"What's standing in the way is a greater appreciation of the importance of clean air, and then the second is money, of course," Marr said.

Building a Cleaner Future for Indoor Air

COVID-19 might give us the momentum needed to make long-term systemic changes and investments for improving our indoor air. "A big possibility—too early to say—is…that the experience with COVID will raise the profile of indoor air quality problems more generally," said Nazaroff.

"When there's not a pandemic, we still have indoor air quality problems, we still have toxic chemicals in our environment, we still have combustion sources. We still have formaldehyde, we still have flu," said Miller. "There are all of these indoor air quality problems that we've been trying to solve for decades, that now we have the obvious attention of most of the public and the scientific community to say, 'Wow, I can't believe we've been overlooking indoor air.'"

"It's not SARS-CoV-2 which is on my mind, because this will pass," Morawska said. "It is the future of infection transmission.… That's why the time is now to put the regulations in place while we are still going through this. That's why I and all the other scientists have put in all the work we can do towards this."

In an editorial published in *Science* in May 2021, Morawska, along with many other experts, proposed a "paradigm shift" in how we combat indoor respiratory infection with building engineering solutions and public health policies.

Jimenez noted that the editorial echoed a call for better ventilation made in 1945 by William F. Wells, a pioneer of aerosol transmission. "Now, in 2021…well, we said the same thing, almost the same words: Ventilation has been neglected."

The design of future buildings should support different ventilation strategies, Morawska said. "Future designs would take into account human health from all aspects of indoor air quality and energy as well."

And we need more than just updated building codes, which establish minimum requirements, Miller said. "What happens with building codes as minimum is [that] everyone just builds to the minimum. So the building is sort of minimally crappy."

Instead, updated environmental legislation is needed, like what we already have for water and outdoor air quality, to protect public health by setting health-based standards requiring the "best available control technology" to reach them, Miller said.

"What I'm stressing as much as possible now is that countries need national indoor air quality standards," Morawska said.

Having standards means enforcing those standards, which in turn means making measurements, which is more complex and costly for indoor air than outdoor air, said Morawska. "It's much more complex but not impossible."

Fortunately, many modern buildings are already equipped with sensors to detect carbon dioxide levels, which can be used as a proxy for ventilation and human-emitted pollutants. Though these sensors are used for HVAC (heating, ventilating, and air-conditioning) systems, such technologies could be implemented for measuring air quality.

In the United States, no government entity at either the state or federal level is clearly responsible for the air quality of our indoor spaces, Nazaroff said. "Outdoor air is undoubtedly a shared resource. We all contribute to its pollution. But no one of us can fix it. Our indoor air has a more complex and nuanced balance between who's responsible for it."

Researchers are cautiously optimistic.

"The greatest success story in history for indoor air pollution has been the shift in smoking behavior," Nazaroff said. Through a multifaceted approach of new rules, changes in social behavior, increased health awareness, and a generational shift, he said, "we're now in a very different place than we were 30 years ago. And that gives me hope."

Places like Finland, South Korea, Sweden, and Taiwan already have legislation for indoor air quality or ventilation. And the Clean Air in Buildings Challenge in the United States highlights recommendations and resources for improving ventilation and indoor air quality, as well as serving as a call to action for reducing risks related to airborne contaminants indoors.

"This is probably the most significant step which I've seen so far, and this hopefully will give other countries direction," Morawska said.

Pollutants and infectious diseases will remain a lingering threat in our indoor air long after the current pandemic peters out. But COVID-19 may have changed how we see, cherish, and protect the air we breathe.

"I worry that people have a short attention span, but it feels like we're potentially on the cusp of an indoor air revolution," Marr said.

> "I worry that people have a short attention span, but it feels like we're potentially on the cusp of an indoor air revolution."

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▶ **Read the article at bit.ly/Eos-indoor-air-pollution**

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ALUMNI PUSH UNIVERSITIES FORWARD ON CLIMATE

A tale of three institutions: How grassroots alumni organizations are encouraging climate action, with mixed results.

By KIMBERLY M. S. CARTIER

Credit: (left to right) wolterke/Depositphotos.com (Harvard); trekandshoot/Depositphotos.com (Penn State); Michael Marsland/campusphotos.yale.edu (Yale)


OLD MAIN

When the graduation ceremony is over and the cap and gown come off, a common interaction many alumni have with their alma maters is ignoring emails soliciting donations or invitations to come back for the annual homecoming game. But younger generations of alumni are recognizing their leverage to drive progressive, top-down action on climate change at their former universities.

"I think that there is undervalued potential for impact by alumni at universities across the country looking toward their board of trustees to effect major change, including climate action," said atmospheric scientist Christa Hasenkopf, director of Air Quality Programs at the Energy Policy Institute of the University of Chicago. "I think it's an underleveraged aspect of the climate action landscape."

Hasenkopf, an alum of Pennsylvania State University (Penn State) in University Park, was recently elected to the university's Board of Trustees, filling one of three open seats this year. She spoke with *Eos* prior to the election and clarified that her statements do not represent the Penn State Board of Trustees.

Penn State Forward, the grassroots organization that supported Hasenkopf's nomination, is one of a few groups to run climate-forward campaigns for university governing boards in the past few years. Some of these campaigns have led to surprising success stories, whereas others have received strong pushback. (Note: I am also an alum of Penn State and voted in the 2022 Board of Trustees election.)

> "We thought that this was a clear place where Harvard as an institution was out of step with Harvard as an interconnected group of people—meaning alumni, students, faculty, and staff."

"It's clear that we need advocates on the highest level to promote the ideas and policies that students, faculty, staff, and community members are behind," said Nora Van Horn, cofounder of Penn State Forward and a current student at Harvard Law School. When grassroots efforts work to put advocates at the highest level, governing boards "can be part of a broader movement for climate action, equity, and university transparency. This requires us to demystify how they work and invite alumni that have been historically excluded to participate in them."

Forward Thinking

Institutions of higher education contribute to anthropogenic climate change in a host of direct and indirect ways. Many colleges and universities still invest money in fossil fuel companies and receive funding from them in return. Most buildings and other campus fixtures like stadiums or shuttle buses are powered by nonrenewable energy sources like coal or natural gas. In some cases, fossil fuel companies direct money to university research on climate solutions—something a large group of climate scientists decried in an open letter earlier this year. Too, given the reputation and credibility universities hold in the public consciousness, their actions can shape public perceptions of what can and should be done to thwart climate change.

But who decides whether a university will divest from fossil fuels or convert its campus power consumption to renewable energy? For the most part these decisions are made by a group of university alumni elected or appointed to governing boards. These boards usually have dozens of members, most of whom are appointed to their positions rather than being elected by popular vote. For boards with elected seats, only a handful are up for election each year. They might be called trustees, overseers, regents, fellows, or governors, but each committee serves a similar purpose: to protect the interests of the university, guide its future direction, and oversee its finances. To meet their legal and fiduciary duties, board members must factor the increasing threat of climate change in to those decisions, Hasenkopf said.

"When it comes to fixing the climate, it can feel so overwhelming for any individual to feel like they can do a single meaningful thing about it," she said. "It feels like it is too large of a problem." In addition, university boards of governance have not always been receptive to feedback from students on contentious issues like climate action, racial justice, or sexual harassment and assault prevention.

"But that's what's so impactful about college alumni getting active in university governance," Hasenkopf said. "For the entire Penn State system to divest its $6.2 billion long-term investment pool, inclusive of both endowed and nonendowed funds, from fossil fuels, you just need a relatively small group of people—the Board of Trustees—to support it. And alumni at many institutions collectively have the power and will to make this happen by electing fellow alumni [to the board] who will push forward climate action efforts."

Alumni-driven efforts to elect climate-forward candidates to governing boards began at Harvard University in Cambridge, Mass. In 2019, Nathán Goldberg Crenier and his peers at Harvard started an organization called Harvard Forward, which aimed to elect candidates to the five open seats on the Board of Overseers in 2020. Goldberg is the cofounder and president of Bluebonnet Data, which organizes volunteer data analysts for progressive political campaigns.

"One of the issues that was a core organizing principle of the group was fossil fuel divestment and climate action in general," Goldberg said. "We thought that this was a clear place where Harvard as an institution was out of step with Harvard as an interconnected group of people—meaning alumni, students, faculty, and staff—and that if we organized a campaign around this issue, that would galvanize a lot of support that Harvard wouldn't be able to ignore."

For institutions of higher education that elect or partially elect their governing boards, electoral processes tend to draw heavily on the alumni base. Candidates are most often nominated by current board members, are elected by networks of alumni from similar backgrounds, and sit on the board for multiyear terms.

Most governing board members are white and male (bit.ly/governing-board). Most also share other characteristics, such as age: "The people who are making decisions about what happens on campus have not been students in 20, 30, 40, 50 years," Goldberg explained. And at Harvard, for example, although its board is more diverse than most with regard to gender and race, the majority of board members have a finance or legal background, which further limits the diversity of viewpoints and experiences brought forward to recognize or solve a problem.

There is also the issue of voter turnout. In the most recent Board of Trustees election at Penn State, 97% of eligible alumni did not vote in board elections, the same percentage as the year before that. "Demographically, you look at who votes, and it's primarily two-to-one men to women, largely folks who graduated in the 70s and 80s and who live toward the center of Pennsylvania," Hasenkopf said. "Even increasing that voter turnout [by] just a couple percent could make a dramatic improvement in representing where alumni want the university to go. Penn State has many campuses across Pennsylvania; it has a large potential for reducing its carbon footprint and making a statement not just for Penn State or Pennsylvania, but really for the nation."

A Hard-Won Battle for Change

A change in board demographics can be hard to come by, but not impossible. Many institutions have a democratic process of nominating independent candidates for board positions. At Penn State, for example, a trustee candidate who receives 250 nominations will be added to a ballot. At Yale, the target was signatures from 3% (about 5,000) of eligible alumni voters.

For the 2020 Harvard board election, the goal was signatures from 1% (about 3,000) of all alumni, a large hurdle for elections with traditionally low voter turnout. Harvard's petition process for board nominations has been successful only a handful of times in the university's history. Notable petition candidates include Archbishop Desmond Tutu in 1989 and former U.S. president (and past president of *Harvard Law Review*) Barack Obama in 1991. Even fewer petition candidates have been elected. (Tutu was elected; Obama was not.)

The Harvard Forward team knew its goal was possible, even if the hurdles were difficult to overcome and had become more bureaucratically arduous after each successful petition.

During Harvard Forward's campaign, the head of the alumni committee that selects overseer candidates spoke out against grassroots campaigns in general, stating that "the role of an Overseer is not to advocate for some particular set of issues that you are expert in or that you care really strongly about." Furthermore, she explained, "effective board members…are thoughtful about the university as a whole, not just the parts that most connect with their personal interests.

The message was clear: "People support this. If they have the option to vote for it, they will."

They check their egos at the door." In a more targeted denouncement, Harvard Alumni Association leaders distributed a letter to alumni accusing the Harvard Forward campaign of raising "copious funding," "leveraging atypical campaigning methods," and setting a "precedent for effectively 'buying' seats on the Board of Overseers [that] threatens to undermine the integrity of the University and its mission." (Harvard Forward refuted the accusations.)

What's more, the system to register a signature is antiquated by current standards: People either must sign by hand on specific university-marked paper and file it in person or download a form from an online submission system, sign by hand, and scan it back in to submit it—no e-signatures allowed. Through the tremendous efforts of volunteers, representatives of Harvard Forward showed up at the 1-day Harvard Alumni Association networking event that takes place in cities around the world. "We got volunteers to go to events in Singapore, in Berlin, in Lima, in Mexico City, Boston, New York, L.A.," Goldberg said, "and tell people in person, face to face, 'Hey, you probably don't know how our governance works, but we have a chance to elect people that stand for something.'" On that day alone, the group collected more than half of the signatures they needed.

Overall, Harvard Forward collected around 4,500 signatures for each of its five candidates in 2020. When voting time came, three of those candidates won seats on the Board of Overseers.

Even Harvard Forward leaders were surprised at their success. "We did not even have a press release version ready for winning three seats," Goldberg said. "It was a huge win." The message was clear, Goldberg continued: "People support this. If they have the option to vote for it, they will."

Less than a year later, Harvard announced that the university would not renew its investment in fossil fuels, a reversal of its earlier position. The school is moving toward fossil fuel divestment, joining a growing list of more than 1,500 businesses and organizations that have already done so and spurring other universities to follow suit.

One Step Forward, Two Steps Back

It seemed like Harvard Forward's success story was set to repeat itself at Yale in early 2020. Scott Gigante and his peers cofounded Yale Forward, a student- and alumni-led campaign inspired by and modeled after Harvard Forward. "They had built a lot of the infrastructure that we needed to start Yale Forward in a quick and easy way," Gigante said. "We thought that this was an underleveraged mechanism of moving our society to address the climate crisis." Gigante is a machine learning scientist at Immunai, a company that seeks to map the human immune system to improve health outcomes.

> "When your opponent controls the rules of the game, it's very hard to play to win."

Yale Forward's climate goals were similar to those of its Harvard predecessor: Make Yale carbon neutral by 2030, prioritize climate action at the highest university levels, and fully divest from fossil fuels as soon as possible.

The group's candidate for The President and Fellows of Yale College, or the Yale Corporation, was 2015 forestry and environmental studies alum Maggie Thomas, who had been a climate adviser on Sen. Elizabeth Warren's (D-Mass.) 2020 presidential campaign. The organization received enough signatures to get Thomas on the 2021 ballot, but she later had to withdraw her name when she was appointed chief of staff to National Climate Advisor Gina McCarthy. Yale Forward shifted its efforts to the 2022 election with environmental management alum Zoraya Hightower, who also received enough petition signatures to be on the ballot.

But a day before the 2021 election and shortly after Hightower announced her intent to run the following year, the university announced that it was suspending the petition process indefinitely.

"There was quite a lot of outrage and disappointment," Gigante said. "I heard from a lot of alumni personally [who] said to me, 'I may not agree with the candidates' policies, but I am 100% in favor of them being able to get on the ballot and make their positions known and being able to vote on that.'"

The official statement from the Yale Corporation does not mention Yale Forward by name, although it does call attention to "issues-based candidacies, with intense campaigning by petitioners who are materially supported by organizations that seek to advance specific platforms." Minutes from the closed meeting during which the decision was made are embargoed until 2071. Gigante, however, believes the move came in retaliation for the slew of petition candidates in 2021 and 2022—there were five over 2 years. Before that, the last successful petition candidate was William Horowitz, Yale's first Jewish trustee, who was elected in 1964. (A few other petition candidates made it onto the ballot since Horowitz, but none was elected.)

Even Harvard Forward's 2020 success did not come without consequence to the university's electoral process. After that election, the university changed the rules so that only six out of the 30 members of the board could be elected via the petition process. Harvard Forward went on to successfully nominate and elect a fourth candidate to the Board of Overseers in 2021; the organization chose not to run a 2022 campaign as it reevaluated its future path.

Gigante said his group expected the Yale Corporation to respond at a level similar to that of the board at Harvard. Losing the petition process entirely was "pretty extraordinary and much, much stronger retaliation than we ever would have expected," he said. Lacking a democratic process to nominate candidates for the Yale Corporation, the group has shifted its efforts to getting that process reinstated.

Despite the setbacks, Gigante believes that Yale Forward's efforts have led to some small progress in bringing climate and other environmental issues to the fore at Yale. The school announced new principles for fossil fuel divestment, and Fred Krupp, head of the Environmental Defense Fund, was elected to the university's board this year through the traditional, nonpetition process.

"When your opponent controls the rules of the game, it's very hard to play to win," Gigante said. "That said, we're not going to stop advocating for the interests of alumni who care about climate action, who care about transparency in governance, who care about representation of those young alumni and diverse alumni."

Surprisingly Quick Success

The 2022 election was Penn State Forward's first attempt at getting independently nominated candidates on the school's governing board—the organization ran three candidates for three open alumni seats. Van Horn said that Penn State Forward received a lot of help and advice from Goldberg and others at Harvard Forward on how to get the campaign started. The group's members took heart at the success of their Harvard counterparts and learned to temper their hopes after seeing the pushback at Yale.

Penn State Forward was cautiously optimistic during the campaign, Hasenkopf explained. Maybe the group would receive one nomination that year, she recalled thinking, but it would probably take a few years to build the awareness and momentum to actually get a candidate elected.

But in the end, all three of Penn State Forward's candidates were successfully nominated, and one, Hasenkopf, was elected. "I was very surprised when they called my name as one of the three winners of the election," she said. "Even more than surprise, though, I felt hope for the grassroots issues and ideas our student- and young alumni–run campaign stood for: achieving educational equity, taking climate action, advancing student health and safety, and ensuring transparent and inclusive governance. Clearly, these issues resonated with the wider Penn State alumni network."

Thus far, the Penn State Board of Trustees has responded positively to Hasenkopf's election and climate-forward goals. "Climate change is recognized as one of the most important issues of our time and Penn State has faculty and top experts working to address the complex challenges that we are facing worldwide," board chair Matt Schuyler said in a statement provided to *Eos* on behalf of the Penn State Board of Trustees. "All members of the Board of Trustees have an opportunity to discuss and engage on topics that are critical to the mission and goals of the University."

Climate scientists at Penn State have also been encouraged by the organization's success and expressed hope that their university will soon announce progressive climate action.

"A few years ago, a student group gave the administration at Penn State coal in a metaphorical holiday stocking as a comment on how little the university was doing to address climate issues," said Sue Brantley, a Penn State geoscientist. Advocacy from students, staff, and faculty has pushed the university toward lowering its carbon footprint, but Hasenkopf's election to the Board of Trustees is a big leap forward, she said. "Penn Staters now anticipate that the university will accelerate its proactive climate decisionmaking. What is truly exciting about this is that Penn State Forward is pushed by our younger alumni finding their political voice…on our campus."

"Wise use of [climate] knowledge will give us a larger economy with more jobs, improved health, and greater national security in a cleaner environment more consistent with the Golden Rule," said Penn State climate scientist Richard Alley. "Huge, critically important parts of the future will rest on research from universities and colleges, will be built and implemented by students educated at universities and colleges, and [will be] helped along by service from those universities and colleges. So getting universities and colleges into the lead and keeping them there is important for us, our students, and the broader world. That applies to Penn State and to all other institutions of higher learning."

Paving the Way Forward

Hasenkopf's term on the Board of Trustees began on 1 July and will last 3 years. In addition to advancing the climate platform she ran on, she hopes that her election serves to raise awareness about how alumni can participate in the university governance process. At Penn State, people who have voted in the past automatically receive a ballot, but "those who just graduated or have never voted before don't have a great way to know the elections are even going on," she said.

One of the most direct ways alumni can contribute to large-scale climate change action at their alma maters is to vote in elections like these.

"There are more than 700,000 living Penn State alumni, a wealth of brainpower," Hasenkopf said. "With only 3% participating in elections, we barely access our biggest resource—alumni!—for our elections, and I'd like to see that change." This will help ensure that people from the generations most affected by climate change are also the ones making decisions about how to fight it, she added.

Van Horn added that regardless of the results of the election, "one of the outcomes has been that the dialogue has shifted. Because [when] there are candidates [who] are running on climate action, candidates [who] in past elections would never have to talk about climate change are now being called to the table to engage in that dialogue. And even if they don't have as ambitious goals as we do…they're still called into that really important conversation about what Penn State can and should be doing." Penn State Forward is planning to run more candidates in the next election, she said, and the team is excited to build on its success.

Goldberg expressed how proud he was that Harvard Forward was able to serve as a model for the Yale and Penn State organizations. "I see it as an interconnected family of campaigns," he said. He hopes that alumni networks at more schools will come out of the woodwork wanting to take similar action and said the team members at Harvard Forward are ready to offer advice based on their experience if needed.

And for alumni who want to follow in Hasenkopf's footsteps and seek a position on a governing board, her best advice is this: "Do it!" she said. "I hope more scientists consider taking on leadership roles at institutions of higher learning—or in society at large."

Learn More

Harvard Forward: www.harvardforward.org/

Harvard Board of Overseers: www.harvard.edu/about/leadership-and-governance/board-of-overseers/

Yale Forward: www.yaleforward.org/

The Yale Corporation: www.yale.edu/board-trustees/

Penn State Forward: www.psuforward.org/

Pennsylvania State University Office of the Board of Trustees: trustees.psu.edu/

Global Fossil Fuel Divestment Commitments Database: divestmentdatabase.org/

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Editor's note: The author is an alum of Pennsylvania State University and voted in the 2022 Board of Trustees election.

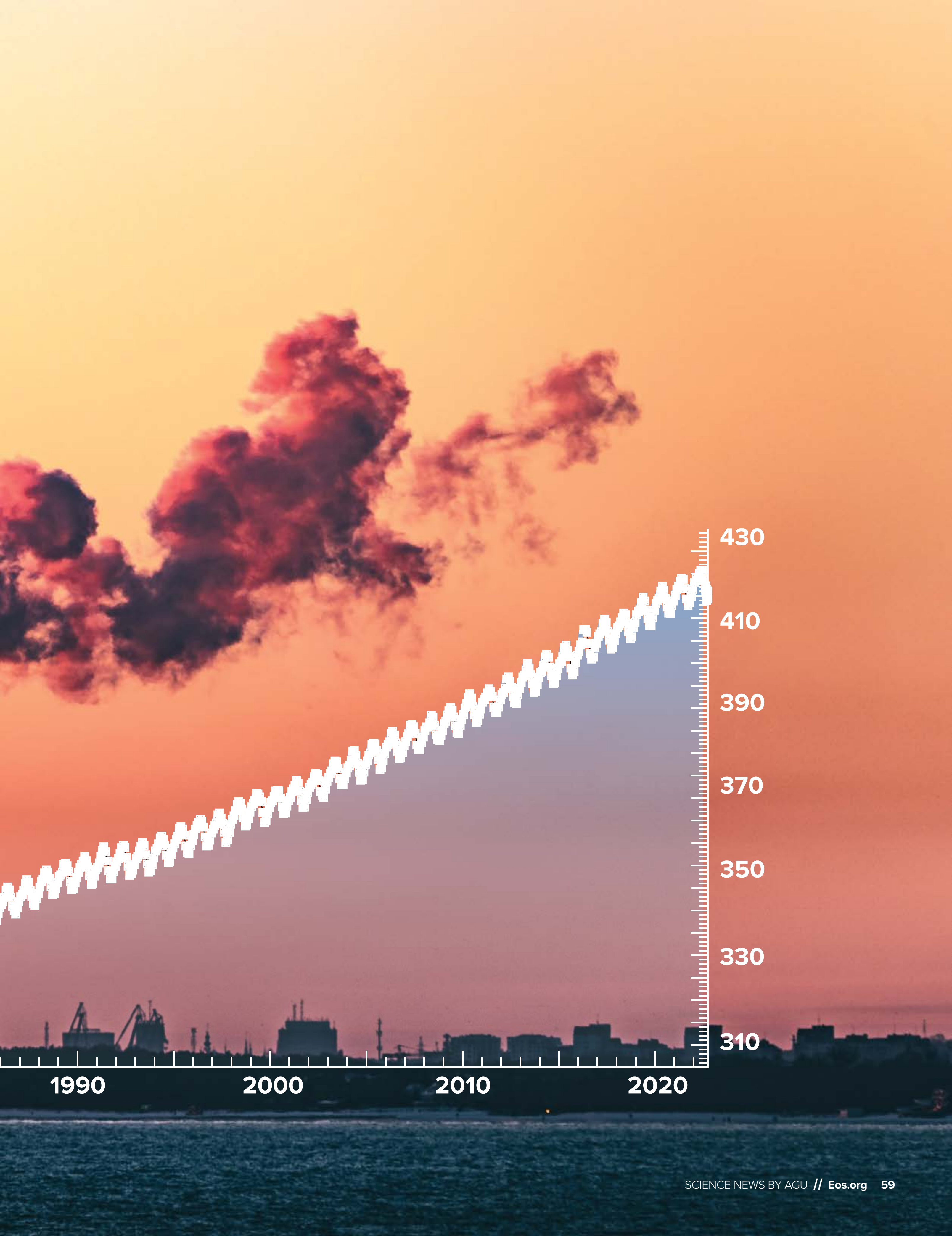
▶ **Read the article at bit.ly/Eos-alumni-climate-push**

SIMPLER PRESENTATIONS **OF CLIMATE CHANGE**

By John Aber
and
Scott V. Ollinger

The basics of climate change have been known for a long time. Focusing on key points of the settled science provides clear communication and a platform for further inquiry.

Since 1958, the "Keeling curve" has charted steadily rising atmospheric carbon dioxide concentrations on the basis of measurements at an observatory on Mauna Loa, Hawaii. Photo credit: Marek Piwnicki/Unsplash


430
410
390
370
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310
1990
2000
2010
2020

Has this happened to you? You are presenting the latest research about climate change to a general audience, maybe at the town library, to a local journalist, or even in an introductory science class. After presenting the solid science about greenhouse gases, how they work, and how we are changing them, you conclude with "and this is what the models predict about our climate future..."

At that point, your audience may feel they are being asked to make a leap of faith. Having no idea how the models work or what they contain and leave out, this final and crucial step becomes to them a "trust me" moment, which can be easy to deny.

This problem has not been made easier by a recent expansion in the number of models and the range of predictions presented in the literature. One recent study making this point is that of *Hausfather et al.* [2022], which presents the "hot model" problem: Some of the newer additions to the Coupled Model Intercomparison Project Phase 6 (CMIP6) predict global temperatures above the range presented in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6). The authors present a number of reasons for, and solutions to, the hot model problem.

Models are crucial in advancing any field of science. They represent a state-of-the-art summary of what the community understands about its subject. Differences among models highlight unknowns on which new research can be focused.

As questions are answered and models evolve, they should not only reproduce past measurements but also begin to produce similar projections into the future.

But Hausfather and colleagues make another point: As questions are answered and models evolve, they should also converge. That is, they should not only reproduce past measurements but also begin to produce similar projections into the future. When that does not happen, it can make "trust me" moments even less convincing.

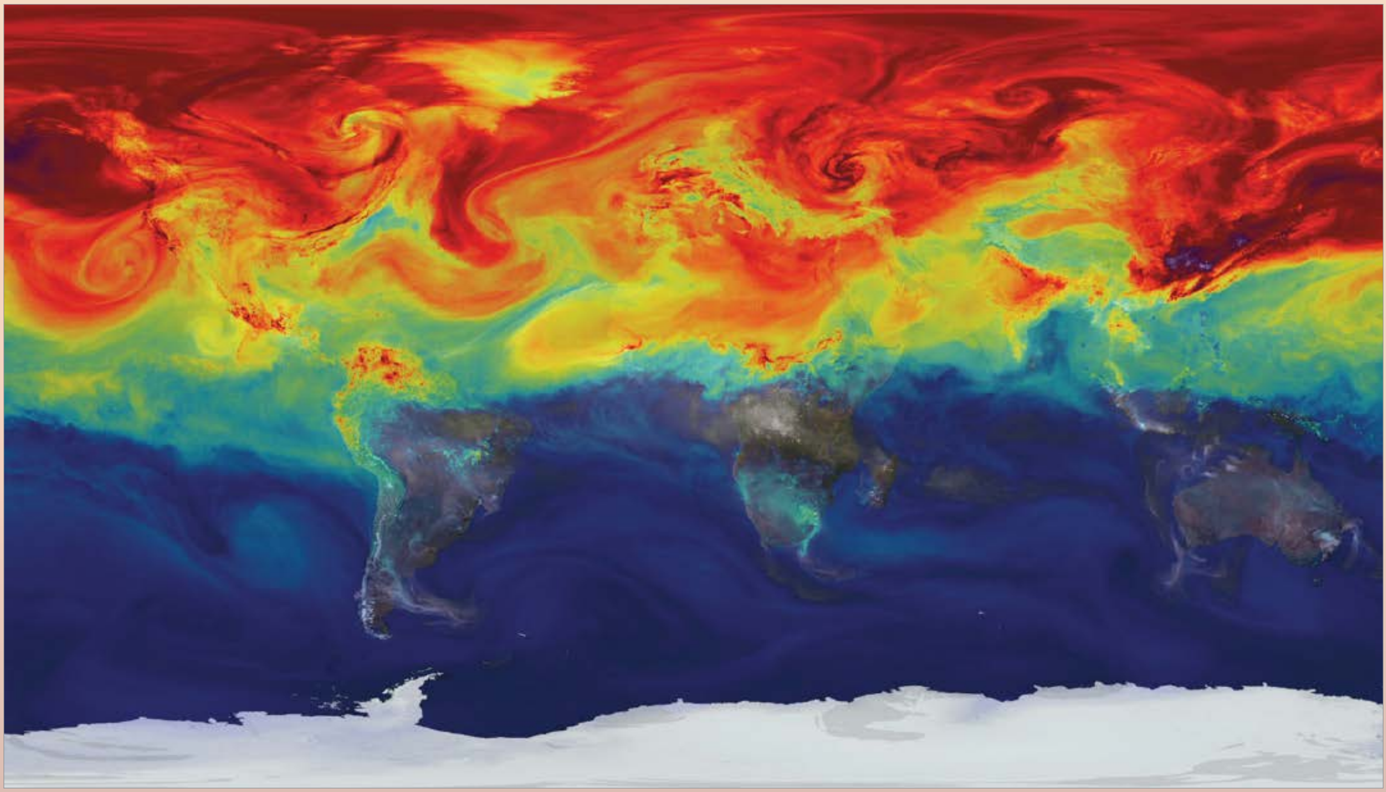
Are there simpler ways to make the major points about climate change, especially to general audiences, without relying on complex models?

We think there are.

Old Predictions That Still Hold True

In a recent article in *Eos*, Andrei Lapenis retells the story of Mikhail Budyko's 1972 predictions about global temperature and sea ice extent [*Budyko*, 1972]. Lapenis notes that those predictions have proven to be remarkably accurate (bit.ly/Eos-global-warming-forecast). This is a good example of effective, long-term predictions of climate change that are based on simple physical mechanisms that are relatively easy to explain.

Many other examples go back more than a century. These simpler formulations don't attempt to capture the spatial or temporal detail of the full models, but their success at predicting the overall influence of



Atmospheric carbon dioxide concentrations in April 2006, with warmer colors representing higher concentrations, are depicted in this snapshot from a simulation of the gas's movement through the atmosphere performed using NASA's Goddard Earth Observing System model, version 5. Credit: William Putman/NASA Goddard Space Flight Center rising carbon dioxide (CO_2) on global temperatures makes them a still-relevant, albeit mostly overlooked, resource in climate communication and even climate prediction.

One way to make use of this historical record is to present the relative consistency over time in estimates of equilibrium carbon sensitivity (ECS), the predicted change in mean global temperature expected from a doubling of atmospheric CO_2. ECS can be presented in straightforward language, maybe even without the name and acronym, and is an understandable concept.

Estimates of ECS can be traced back for more than a century (Table 1), showing that the relationship between CO_2 in the atmosphere and Earth's radiation and heat balance, as an expression of a simple and straightforward physical process, has been understood for a very long time. We can now measure that balance with precision [e.g., *Loeb et al.*, 2021], and measurements and modeling using improved technological expertise have all affirmed this scientific consistency.

Table 1. Selected Historical Estimates of Equilibrium Carbon Sensitivity (ECS)

DATE	AUTHOR	ECS (°C)	NOTES
1908	Svante Arrhenius	4	In *Worlds in the Making*, Arrhenius also described a nonlinear relationship between carbon dioxide (CO_2) and temperature.
1938	Guy Callendar	2	Predictions were based on infrared absorption by CO_2, but in the absence of feedbacks involving water vapor.
1956	Gilbert Plass	3.6	A simple climate model was used to estimate ECS. Plass also accurately predicted changes by 2000 in both CO_2 concentration and global temperature.
1967	Syukuro Manabe and Richard T. Wetherald	2.3	Predictions were derived from the first climate model to incorporate convection.
1979	U.S. National Research Council	2–3.5	The results were based on a summary of the state of research on climate change. The authors also concluded that they could not find any overlooked or underestimated physical effects that could alter that range.
1990 to present	Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report	3 (2.5–4)	Numerous IPCC reports have generated estimates of ECS that have not changed significantly across the 30-year IPCC history.
2022	Hausfather et al.	2.5–4	ECS was derived by weighting models based on their historical accuracy when calculating multimodel averages.
2022	Aber and Ollinger	2.8	A simple equation derived from Arrhenius [1908] was applied to the Keeling curve and Goddard Institute for Space Studies temperature data set.

Settled Science

Another approach for communicating with general audiences is to present an abbreviated history demonstrating that we have known the essentials of climate change for a very long time—that the basics are settled science.

The following list is a vastly oversimplified set of four milestones in the history of climate science that we have found to be effective. In a presentation setting, this four-step outline also provides a platform for a more detailed discussion if an audience wants to go there.

- 1850s: Eunice Foote observes that, when warmed by sunlight, a cylinder filled with CO_2 attained higher temperatures and cooled more slowly than one filled with ambient air, leading her to conclude that higher concentrations of CO_2 in the atmosphere should increase Earth's surface temperature [*Foote*, 1856]. While not identifying the greenhouse effect mechanism, this may be the first statement in the scientific literature linking CO_2 to global temperature. Three years later, John Tyndall separately develops a method for measuring the absorbance of infrared radiation and demonstrates that CO_2 is an effective absorber (acts as a greenhouse gas) [*Tyndall*, 1859; 1861].
- 1908: Svante Arrhenius describes a nonlinear response to increased CO_2 based on a year of excruciating hand calculations actually performed in 1896 [*Arrhenius*, 1896]. His value for ECS is 4°C (Table 1), and the nonlinear response is summarized in a simple one-parameter model.
- 1958: Charles Keeling establishes an observatory on Mauna Loa in Hawaii. He begins to construct the "Keeling curve" based on measurements of atmospheric CO_2 concentration over time. It is amazing how few people in any audience will have seen this curve.
- Today: A data set of global mean temperature from NASA's Goddard Institute for Space Studies (GISS) records the trajectory of change going back decades to centuries using both direct measurements and environmental proxies.

> ***One way to make use of the historical record is to present the relative consistency over time in estimates of equilibrium carbon sensitivity (ECS), the predicted change in mean global temperature expected from a doubling of atmospheric CO_2. ECS is an understandable concept.***

The last three of these steps can be combined graphically to show how well the simple relationship derived from *Arrhenius*'s [1908] projections, driven by CO_2 data from the Keeling curve, predicts the modern trend in global average temperature (Figure 1). The average error in this prediction is only 0.081°C, or 8.1 hundredths of a degree.

A surprise to us was that this relationship can be made even more precise by adding the El Niño index (November–January (NDJ) from the previous year) as a second predictor. The El Niño–Southern Oscillation (ENSO) system has been known to affect global mean temperature as well as regional weather patterns. With this second term added, the average error in the prediction drops to just over 0.06°C, or 6 hundredths of a degree.

It is also possible to extend this simple analysis into the future using

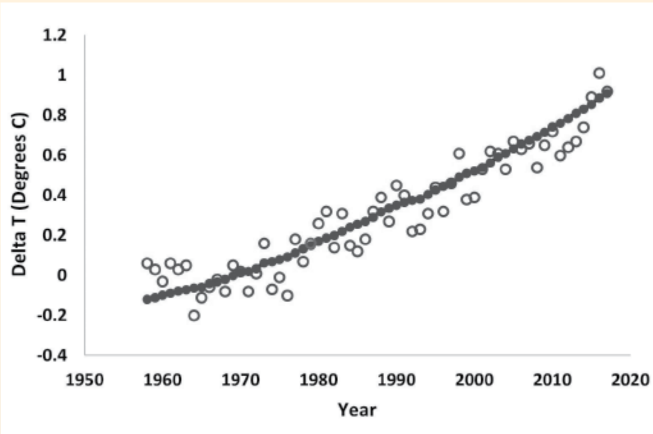


Fig. 1. Measured changes in global mean temperature (Delta T) from Goddard Institute for Space Studies data (open circles) are compared here with predictions (solid circles) from a one-parameter model derived from calculations performed by Svante Arrhenius in 1896 and driven by Keeling curve carbon dioxide (CO_2) data. Temperature changes are relative to the baseline average temperature for the period 1951–1980.

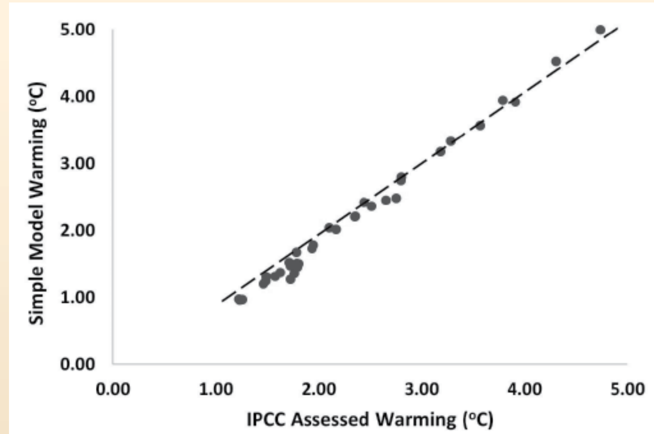


Fig. 2. Values of assessed global mean warming through the year 2100 from four frequently cited scenarios included in the Intergovernmental Panel on Climate Change's Sixth Assessment Report are compared here with predictions from the simple model used in Figure 1 driven by the projected CO_2 concentrations from the same four scenarios. The dashed line indicates a 1:1 relationship, showing close agreement between the two estimates.

the same relationship and IPCC AR6 projections for CO_2 and "assessed warming" (results from four scenarios combined; Figure 2).

Although CO_2 is certainly not the only cause of increased warming, it provides a powerful index of the cumulative changes we are making to Earth's climate system.

In this regard, it is interesting that the "Summary for Policymakers" [*Intergovernmental Panel on Climate Change*, 2021] from the most recent IPCC science report also includes a figure (Figure SPM.10, p. 28) that captures both measured past and predicted future global temperature change as a function of cumulative CO_2 emissions alone. Given that the fraction of emissions remaining in the atmosphere over time has been relatively constant, this is equivalent to the relationship with concentration presented here.

That figure also presents the variation among the models in predicted future temperatures, which is much greater than the measurement errors in the GISS and Keeling data sets that underlie the relationship in Figure 1.

A presentation built around the consistency of ECS estimates and the four steps clearly does not deliver a complete understanding of the changes we are causing in the climate system, but the relatively simple, long-term historical perspective can be an effective way to tell the story of those changes.

Past Performance and Future Results

Projecting the simple model used in Figure 1 into the future (Figure 2) assumes that the same factors that have made CO_2 alone such

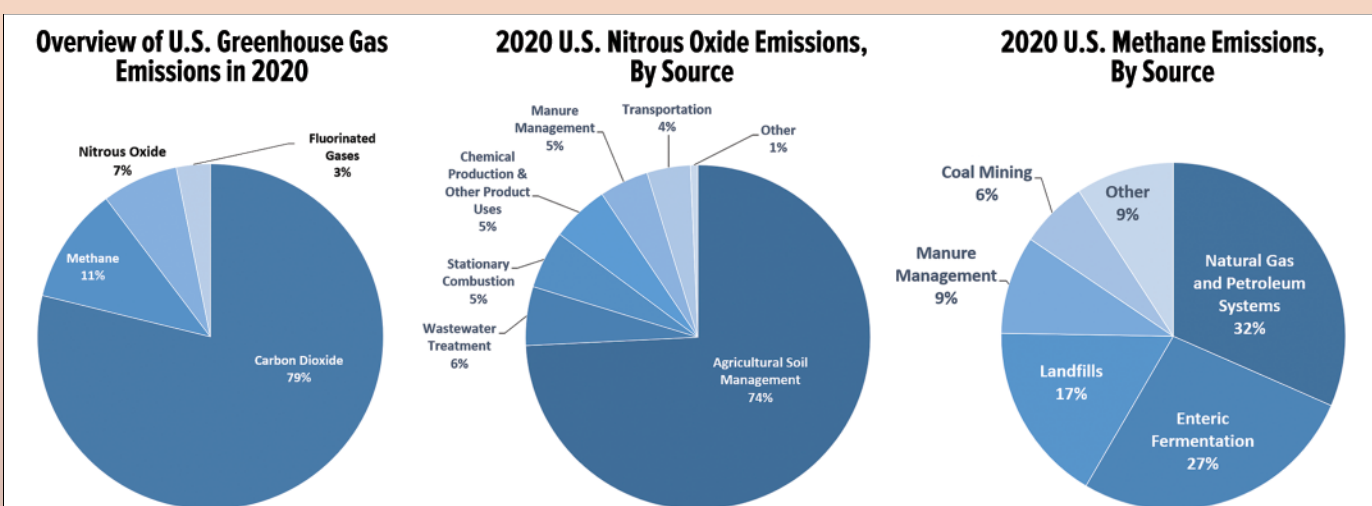


Fig. 3. EPA-reported total U.S. greenhouse gas emissions in 2020 (left) amounted to 5,981 million metric tons of CO_2 equivalent, led by emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O). Major sources of N_2O (center) and CH_4 (right) emissions are also shown. Credit: EPA

a good index of climate change to date will remain in place. But we know there are processes at work in the world that could break this relationship.

For example, some sources now see the electrification of the economic system, including transportation, production, and space heating and cooling, as part of the path to a zero-carbon economy [e.g., *Gates*, 2021]. But in one major economic sector, energy production is not the dominant process for greenhouse gas emissions, and carbon dioxide is not the major greenhouse gas. That sector is agriculture.

When and if the simple relationship derived from Arrhenius's calculations does fail as an accurate index of changes in mean global temperature, it will still provide a useful platform for explaining what has happened and why.

The U.S. Department of Agriculture has estimated that agriculture currently accounts for about 10% of total U.S. greenhouse gas emissions, with nitrous oxide (N_2O) and methane (CH_4) being major contributors to that total. According to the EPA (Figure 3), agriculture contributes 79% of N_2O emissions in the United States, largely from the production and application of fertilizers (agricultural soil management) as well as from manure management, and 36% of CH_4 emissions (enteric fermentation and manure management—one might add some of the landfill emissions to that total as well).

If we succeed in moving nonagricultural sectors of the economy toward a zero-carbon state, the relationships in Figures 1 and 2 will be broken. The rate of overall climate warming would be reduced significantly, but N_2O and CH_4 would begin to play a more dominant role in driving continued greenhouse gas warming of the planet. We would then need more complex models than the one used for Figures 1 and 2. But just how complex?

In his recent book *Life Is Simple*, biologist Johnjoe McFadden traced the influence across the centuries of William of Occam (~1287–1347) and Occam's razor as a concept in the development of our physical understanding of everything from the cosmos to the subatomic structure of matter [*McFadden*, 2021]. One simple statement of Occam's razor is, Entities should not be multiplied without necessity.

This is a simple and powerful statement: Explain a set of measurements with as few parameters, or entities, as possible. But the definition of necessity can change when the goals of a model or presentation change. The simple model used in Figures 1 and 2 tells us nothing about tomorrow's weather or the rate of sea level rise or the rate of glacial melt. But for as long as the relationship serves to capture the role of CO_2 as an accurate index of changes in mean global temperature, it can serve the goal of making plain to general audiences that there are solid, undeniable scientific reasons climate change is happening.

Getting the Message Across

If we move toward an electrified economy and toward zero-carbon sources of electricity, the simple relationship derived from Arrhenius's calculations will no longer serve that function. But when and if it does fail, it will still provide a useful platform for explaining what has happened and why. Perhaps another, slightly more complex model will be created for predicting and explaining climate change that involves three gases.

No matter how our climate future evolves, simpler and more accessible presentations of climate change science will always rely on and begin with our current understanding of the climate system. Complex, detailed models will be central to predicting our climate future (Figure 2 here would not be possible without them), but we will be more effective communicators if we can discern how best to simplify that complexity when presenting the essentials of climate science to general audiences.

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▶ **Read the article at bit.ly/Eos-climate-change-presentations**

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For-profit conferences that masquerade as legitimate academic events but lack trusted selection and peer review processes are becoming more common. Here's why that matters.

Olegkalina/Depositphotos

THE ALARMING RISE OF PREDATORY CONFERENCES

BY MATTHIEU CHARTIER

Thorough evaluation and expert peer review of research are at the core of academic and scientific integrity. When researchers attend a conference or cite a paper, they do so with confidence that these events and publications are operated in good faith and have undergone a trusted review process to ensure, as much as possible, that the content they distribute is sound. Scientists who present their work at these conferences similarly trust that doing so enhances, rather than detracts from, their professional reputations. Meanwhile, media outlets that report on conferences expect that not only do the proceedings offer fresh insights on new research, but also the research has been vetted for its methodology and significance.

These expectations and assumptions were long safe: The legitimacy of publications and events organized by well-intentioned, competent groups with genuine interest in advancing science were not in question. However, predatory journals began to appear in the early 2000s and have become more common over the past decade, signaling that unscrupulous organizations are willing to push scientific integrity aside for the sake of profit. These journals offer researchers easy access to publishing, for a fee, while dismissing typical quality controls like rigorous peer review or checks for plagiarism.

Unfortunately, it is no longer safe to assume that a conference is genuine without doing proper background research into its organizers and sponsors.

More recently, the occurrence of similarly predatory (or "fake") conferences has increased across numerous scientific disciplines, including in the Earth and space sciences. Unfortunately, it is no longer safe to assume that a conference is genuine without doing proper background research into its organizers and sponsors.

My colleagues and I have witnessed the growing trend of predatory conferences both firsthand and through discussions with clients. Our company provides technology and software solutions that help scientific conference organizers manage elements of their event planning, from participant registration to the peer review process. Admittedly, we have a vested interest in the success of legitimate conferences, with whom we do business, so the growth of predatory conferences has repercussions for us as a company. More important, however, is that these activities harm researchers who fall prey to them, and they threaten to damage public perceptions of and trust in science.

A Growing Problem

For most academics, attending scholarly conferences is a traditional part of advancing one's research and growing one's career. For early-career researchers especially, these events are an important way to build CVs, develop professional brands, share research, and gather valuable feedback. Conferences also present unique opportunities to network with like-minded people who may later become colleagues, research partners, employers, or funders. Researchers and others in academia, industry, government, and nonprofit organizations can mingle and share ideas during formal sessions and gatherings, in hallways and lobbies between sessions, over dinner, or, more recently, in online discussions hosted as part of remote or hybrid conferences.

In short, such meetings are organized to bring together scholars whose work overlaps and to create an environment for idea-sharing and research development. This is not the case when it comes to fake conferences, which unfortunately often look and sound superficially like standard academic conferences. Their websites boast of renowned speakers, and they advertise events hosted at reputable venues and backed by high-profile sponsors.

Although the term "fake" may suggest that these are not real events, they actually do take place. However, they are typically not nearly as well organized as advertised, nor does their content live up to the billing. Participants often find ill-attended events that lack the prestigious keynote speakers advertised and have few learning or networking opportunities.

Predatory academic conferences are more common than you may think. As recently as 5 years ago, more such conferences were reportedly available to scientific researchers than genuine events held by scholarly groups that follow standard peer review processes.

In a recent study conducted over a 2-year period by the InterAcademy Partnership (IAP), of more than 1,800 researchers working in 112 countries who were surveyed anonymously, 80% reported that predatory journals and conferences either were a serious problem in their country already or were becoming a serious problem. Of those surveyed, 11% acknowledged having published in a predatory journal, 2% knowingly and 9% who were completely unaware at the time. Meanwhile, 4% acknowledged having participated in a predatory conference, with 1% attending knowingly and 3% unaware. Another 6% of respondents were uncertain whether they had attended a predatory conference.

Predatory conferences are big business, organized with the primary goal of profit generation. In particular, they are set up to scam people out of registration and publishing fees, and as a result, organizers are known to accept every proposed submission regardless of merit, as long as it is accompanied by a registration fee. The conferences thus lack the scientific and editorial integrity required of a legitimate academic meeting.

Most of these events are being organized by a relatively small number of large, international organizations, although smaller companies have recently entered the industry. Senthil Gopinath, CEO of the International Congress and Convention Association, a trade group for the association meetings industry, has commented on the scale and impact of predatory conferences: "Tens of thousands of terrible quality and sometimes fraudulent conferences are today being promoted around the world, which presents an industrial-scale challenge to bona fide associations and their quality education programs. It's a global phenomenon, which today impacts negatively on almost every scientific discipline."

Wasted Resources, Bad Science, and Eroded Trust

Extrapolating from its recent survey results, the IAP estimated that at least 1 million researchers globally have fallen prey to predatory journals and conferences, and that these activities have wasted billions of dollars in research funding. For example, money is wasted on time and materials spent on research published in predatory journals as well as on registration and travel expenses to attend predatory conferences. The IAP report also noted that scientists sometimes suffer significant reputational damage and emotional stress at the realization that they've been "duped or scammed."

While researchers at all career levels can fall prey to these predatory practices, early-career academics may be particularly at risk, lured by tempting opportunities to gain experience presenting their work and build their resumes and careers amid competitive "publish or perish" environments. These researchers, who often struggle to find funding, waste their scarce and hard-earned money on expenses related to attending or presenting at a fake conference. Furthermore, the IAP report points out that "researchers in low- and middle-income countries were more likely to report they had used predatory practices, or not know if they had, than those in higher-income ones." This trend could be explained by predatory conference organizers targeting countries where researchers have fewer opportunities, among other reasons.

As recently as 5 years ago, more predatory conferences were reportedly available to scientific researchers than genuine events held by scholarly groups.

The existence of predatory conferences and journals—and the unvetted science they present—risks damaging the legitimacy of academia and the scientific enterprise in the eyes of policymakers, community leaders, and those in the public who rely on scientific expertise but may not be equipped to distinguish what is or is not solid science. The more these people's work, lives, and decisions are undermined by bad science, the less faith they are likely to have in credible research. And if they do not trust the work being published by academic sources, where will they turn for information?

The growth of predatory conferences and journals may also offer more opportunities for underqualified and underinformed commentators to pass off bad science as legitimate, whether on purpose or not. This is especially true in an era when misinformation is rampant; the trustworthiness of unbiased, reliable sources of scientific information is increasingly questioned; and anyone with a social media account can potentially build an audience of millions. In this environment, the sanctity of research-based, peer-reviewed scientific findings is vitally important.

Considering the costs to researchers and to research integrity, it's clear that the academic community must face predatory conferences head-on.

In a few isolated incidents, legal action has been taken against the organizers of predatory conferences. For example, in 2016, the U.S. Federal Trade Commission (FTC) filed charges against several companies, alleging that they lied to researchers about their conferences and publications. And in 2019, a federal court found the companies' claims that research submissions underwent a rigorous peer review process and review by editorial boards made up of well-respected academics to be false; the court ordered them to pay more than $50 million to resolve the FTC charges.

There are steps researchers can take and telltale signs to look for that will help determine whether an event is worth their time and money.

Despite the occasional legal and financial penalties doled out to predatory conference organizers for their practices, not much can be done from an institutional perspective to protect the academic community. Perhaps the most effective means to tackle the problem is for researchers to recognize and avoid predatory conferences for themselves.

Recognizing and Avoiding Predatory Conferences

Predatory conferences can be difficult to differentiate from legitimate ones. However, there are steps researchers can take and telltale signs to look for that will help determine whether an event is worth their time and money. The following approaches may be especially useful:

Research the organization putting on the event. Chances are you know of the major think tanks and organizations that would organize legitimate events in your field of expertise. If a conference organizer is a private company or an organization you don't know about, or you're considering an event outside your primary field, do some digging. Research the organization online and search for lists of predatory conferences that have been identified. Even if the event you're considering is not listed, if the organization hosting it has been called out for organizing predatory conferences in the past, it's reasonable to be suspicious. You can also check the website Think. Check. Attend. (thinkcheckattend.org), which aims to help researchers judge the legitimacy and academic credentials of conferences to help them determine whether they are legitimate and worthy of pursuit.

Spend some time on the event website. Legitimate academic conferences build a website that's an extension of their main site. If a conference's website URL is completely unrelated to an academic or reputable professional organization, that's a red flag.

Consider the sponsors. Some predatory conferences list big-name sponsors to create the appearance of a well-funded, well-planned event. But are the sponsors mentioned relevant to the topic of the conference? If you're considering attending a conference in the Earth and space sciences but the main sponsors appear to be medical or biotechnology companies, for example, it would be a good idea to investigate further, perhaps by contacting the supposed sponsoring organizations to verify their participation.

Connect with the event organizers. If you're skeptical about the legitimacy of an event, reach out to the organizers. Ask about their peer review process and details related to the venue and agenda. Organizers of a legitimate conference will be communicative and happy to clarify any questions you have about their event. If their reply is suspicious, or they don't reply at all, chances are you're better off sitting out the event.

Academic and professional conferences offer important avenues to gain experience, learn about cutting-edge research, gather feedback about one's own work, and network with peers and potential collaborators, employers, and funders. Predatory conferences must not deter us from participating in conferences as a whole, but it is increasingly vital to do our research before sending off that registration fee. Funding for scientific and technical innovation, researchers' reputations, and public trust in the reliability of science are all at stake.

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Prince Sultan Bin Abdulaziz International Prize for Water

Recognizing Innovation

Winners for the 10th Award (2022)

Creativity Prize

1) The team led by Thalappil Pradeep (Indian Institute of Technology, Madras, India)
for the creation and successful deployment of environmentally friendly "water positive" nanoscale materials for the affordable, sustainable and rapid removal of arsenic from drinking water. Team members include Avula Anil Kumar, Chennu Sudhakar, Sritama Mukherjee, Anshup, and Mohan Udhaya Sankar.

Dr. Thalappil Pradeep

2) The team led by Dionysios D. Dionysiou (University of Cincinnati, USA)
for the development of innovative advanced oxidation technologies and nanotechnologies for environmental applications, particularly in the removal and monitoring of emerging contaminants. Team members include Abdulaziz Al-Anazi, Wael H.M. Abdelraheem, Jiong Gao, Ying Huang, and Vasileia Vogiazi.

Dr. Dionysios D. Dionysiou

Surface Water Prize

Dennis D. Baldocchi (University of California Berkeley, USA)
for the development and implementation of effective models to understand, evaluate and predict evapotranspiration and water-use efficiency in various environments under climate change conditions.

Dr. Dennis D. Baldocchi

Groundwater Prize

Linda M. Abriola (Brown University, USA)
for pioneering research on toxic Dense Non-Aqueous Phase Liquids (DNAPLs) in groundwater, ranging from the simulation of their fate to effective methods for cleaning contaminated sites.

Dr. Linda M. Abriola

Alternative Water Resources Prize

The team of Menachem Elimelech (Yale University, USA) and Chinedum Osuji (University of Pennsylvania, USA)
for wide-ranging advances in nanostructured materials for next-generation water purification, focusing on implementation issues like manufacturing, sustainability, self-assembly, and biofouling.

Dr. Menachem Elimelech

Dr. Chinedum Osuji

Water Management and Protection Prize

The team led by Matthew McCabe (KAUST, Thuwal, Saudi Arabia)
for employing CubeSat constellations in the sustainable management and security of linked water-food systems, along with estimates of agricultural water use at unprecedented spatial and temporal resolutions and with global coverage. Team members include Bruno Aragon (KAUST) and Rasmus Houborg (Planet Labs, USA).

Dr. Matthew McCabe

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Estimating Uranium and Thorium Abundance with Geoneutrinos

A planet's interior heat comes from two principal sources: leftover energy amassed from collisions between planetesimals during the accretion of the planet and the subsequent decay of radioactive elements embedded within that material.

Uranium (U), thorium (Th), and potassium have contributed significantly to Earth's internal energy budget, and the magnitude of that contribution is a key constraint on the planet's interior evolution. However, because the elements are located deep within Earth, their abundances have been thus far difficult to estimate.

Abe et al. present new, significantly tighter constraints on the abundances of uranium and thorium measured using a unique observational window: the detection of terrestrial electron antineutrinos. These antineutrinos are emitted during the beta decay of ^{238}U and ^{232}Th and then pass unencumbered through Earth. A tiny fraction of the particles can be measured by an experiment called the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND).

The Kamioka Liquid Scintillator Antineutrino Detector can ascertain the presence of electron antineutrinos produced through the decay of uranium and thorium deep inside Earth when they collide with atomic nuclei. Credit: Research Center for Neutrino Science, Tohoku University

KamLAND, based in Hida, Gifu, Japan, is located 1,000 meters underground in an abandoned mining shaft. It uses a large vat of liquid to induce the beta decay reaction, in which an incoming antineutrino strikes an atomic nucleus and converts a proton to a neutron and a positron. These particles can then be observed by the detector.

KamLAND was originally intended to observe antineutrinos emitted by Japan's commercial nuclear reactors. However, after the 2011 Fukushima nuclear accident, these reactors were all shut down. The sudden absence of artificially produced antineutrinos dramatically increased KamLAND's sensitivity to those of natural origin. In total, the authors present 18 years of data, nearly half of which have been recorded since the shutdown of Japan's reactors.

The researchers compared the observed antineutrino flux with those predicted by three models for the abundance of uranium and thorium within the mantle. These models correspond to three levels of heat added to the interior: low (10–15 terawatts), medium (17–22 terawatts), and high (more than 25 terawatts). They considered two variations of each model: one with radioisotopes distributed uniformly throughout the mantle and one with them concentrated at the core-mantle boundary.

The data exclude both variations of the high-heat model with greater than 97% confidence. This model was constructed to provide the heat necessary to support mantle convection, so the results suggest that our understanding of this convection may require some modification. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL099566, 2022) **—Morgan Rehnberg,** *Science Writer*

Factors in the Severity of Heat Stroke in China

Heat waves are predicted to be more frequent, more intense, and longer lasting as the climate warms. This year, for example, India, Europe, and the United States all experienced record-breaking heat. Not only do heat-related deaths soar during these events, but also heat-related diseases are triggered. Heat stroke, in particular, is a serious condition that can trigger multiple organ tissue injuries, neurological morbidity, and, in some cases, death. In China, recorded data on heat stroke morbidity are lacking. Therefore, the connections between heat stroke and meteorological data, like relative humidity, are difficult to determine at larger, citywide scales.

In a new paper, *Han et al*. collected daily heat stroke search index (HSSI) data along with meteorological data from 2013 to 2020 for 333 Chinese cities to shed light on the relationship between heat stroke and weather conditions. The team discovered that temperature and relative humidity were the most important factors contributing to the severity of heat stroke, with 62% of the HSSI changes caused by temperature and 9% caused by relative humidity. Further, the researchers determined that residents of China may experience heat stroke when temperatures exceed 36°C and relative humidity rises above 58%. In the southern part of the country, low-altitude regions, and coastal cities, the temperature thresholds were a bit higher.

The researchers said that their work shows a connection between meteorological conditions and heat-related diseases, and that geography affects thresholds in those conditions. They noted that their work may help policymakers and government officials create new warning systems for the public. (*GeoHealth*, https://doi.org/10.1029/2022GH000587, 2022) **—Sarah Derouin,** *Science Writer*

Machine Learning Could Revolutionize Mineral Exploration

The Morenci Mine in Arizona is one of the world's largest suppliers of copper and other sought-after minerals. Credit: Stephanie Salisbury/Wikimedia, CC BY 2.0 (bit.ly/ccby2-0)

Twenty-first century technologies, including those central to a low-carbon future, rely on rare earth elements and metals. Many of these sought-after minerals reside in porphyry copper deposits that contain hundreds of millions of metric tons of ore. In addition to copper, these deposits are a source of significant quantities of gold, molybdenum, and rhenium. However, the mining industry has identified and mined most of the world's large and accessible porphyry deposits. Despite growing investment in mineral exploration, the rate of discovery for mineral deposits is decreasing.

In a recently published study, *Zou et al*. present two novel machine learning techniques to identify new, deeply buried porphyry copper deposits by characterizing magma fertility. Fertile magma refers to magma that can form porphyry deposits. Barren magma, in contrast, is not likely to develop rich ores. The authors aimed to improve traditional geochemical indicators plagued by high false-positive rates.

The authors developed two algorithms: random forest and deep neural network. They formulated the models using a global data set of zircon chemistry, which is used to evaluate the porphyry copper deposits in magma. They focused the models on 15 trace elements and validated them with independent data sets from two well-characterized porphyry copper deposits in south central British Columbia, Canada, and Tibet.

Both models resulted in a classification accuracy of 90% or greater. The random forest model exhibited a false-positive rate of 10%, whereas the deep neural network model had a 15% false-positive rate. In comparison, traditional metrics report false positives at a 23%–66% rate.

Europium, yttrium, neodymium, cerium, and other elements emerged as significant indicators of magma fertility. The models' performances indicate that the algorithms can distinguish between fertile and barren magmas using trace element ratios. Model performance was not affected by regional differences or the geologic setting between the evaluation data sets from Canada and Tibet.

As the demand for rare earth elements, minerals, and metals surges, new techniques are required to discover previously unknown deposits. According to the researchers, their results highlight machine learning's promise as a robust, accurate, and effective approach for identifying and locating porphyry copper resources. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2022JB024584, 2022)

—Aaron Sidder, *Science Writer*

Models Oversimplify How Melting Glaciers Deform Land

The retreat of glaciers, like Berg Glacier in Mount Robson Provincial Park in British Columbia, Canada, can change Earth's shape. Credit: Jeffrey Pang/Wikimedia, CC-BY 2.0 (bit.ly/ccby2-0)

Around 21,000 years ago, ice sheets retreated from the Northern Hemisphere, and great swaths of land were unburdened by the weight of glaciers. Even today, Earth's shape is still changing as the land rebounds, causing effects like shoreline migration that are observable on human timescales. This process is called glacial isostatic adjustment (GIA), and although the effect is well documented, the details of how Earth is changing shape have long been opaque.

In a recent paper, *Simon et al.* compare records of sea level change to two common types of GIA models. They find that Maxwell models, which assume that Earth has a constant strength when it rebounds from glacial melting and which have long been used to model GIA, don't fit the sea level data as well as Burgers models, which allow for Earth to be weaker initially and therefore rebound faster at first.

The researchers examined sea level change at around a dozen sites at varying distances from historical ice sheets. Land that was once underneath or close to ice sheets deformed quickly soon after the ice sheet melted—a transient period of quick deformation not readily captured by Maxwell models. These findings have been supported by studies of land deformation after other disturbances, such as earthquakes.

The study is a step toward unifying various types of data on how Earth's shape has changed to produce a comprehensive understanding of what happens when glaciers melt. The results point to the importance of considering short periods of fast deformation soon after conditions change and to an unexpected use for high-quality sea level data. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB023693, 2022) **—Saima May Sidik,** *Science Writer*

How Wildfires Affect Snow in the U.S. West

In places like the Indian Creek watershed in southern Colorado, wildfires have left lasting impacts and affect snow accumulation. Credit: Laura Hempel, hydrologist at the USGS Colorado Water Science Center, Public Domain

Fresh powder does more than support winter sports. Snowmelt flows into streams, where it helps sustain agriculture, supports natural ecosystems, and provides drinking water. Wildfires are threatening snowpacks, but research on the impact on snow water equivalent generally focuses on localized areas, often using varying methods and getting conflicting results.

Giovando and Niemann set about rectifying this situation with data from the Snow Telemetry (SNOTEL) system, which uses automated sensors to measure snow depth and other aspects of weather at hundreds of sites around the western United States. The researchers compared 45 burned SNOTEL sites with similar unburned sites. They found that when burned regions were at their snowiest, they obtained, on average, 13% less water from snow than their unburned counterparts. Snow melted completely 9 days earlier in burned regions compared with unburned areas.

Giovando and Niemann also estimated how climate change alone affects snowmelt by comparing snow at unburned sites before and after fires hit nearby sites. Of these unburned sites, 56% saw their maximum snowpack earlier in the season, and 78% lost their snow earlier in the season. However, 62% of the same regions saw an increase in their maximum snowpack over the time period analyzed.

The results of this study suggest that climate change has affected the timing of snowmelt, and wildfires exacerbate this change and can also have a larger effect on the amount of water obtained from snow. (*Water Resources Research,* https://doi.org/10.1029/2021WR031569, 2022) **—Saima May Sidik,** *Science Writer*

Bangladeshis Feel Increased Consequences of Sedimentation

Bangladesh's Tanguar Haor is a seasonal wetland. Increased sedimentation in the haor is threatening people's lives, livelihoods, and safety. Credit: Mohammad Tauheed, CC BY-NC 2.0 (bit.ly/ccbync2-0)

The haor landscape is a network of bowl-shaped depressions in northern Bangladesh. During monsoon season, up to 12 meters of rain can fall in some parts of the drainage basins feeding the haor, forming wetlands that recede during the dry season.

Sediment has always flowed from the mountains along with the rains, but satellite images show that deposition has increased over the past 6 decades. Increased flooding, mining, deforestation, and poor waterway maintenance are just some of the reasons behind the rise in sedimentation. Regardless of the cause, more than 19 million people living in the region have experienced the sediment's invariably negative—and sometimes even catastrophic—impacts.

In a new study, *Islam et al.* collected information from 180 households in the haor to learn how sediment had affected their lives. Respondents reported a broad variety of detrimental effects. Many were related to agriculture: Sediment can increase soil acidity and thereby decrease land productivity. Sediment also clogs waterways, leading to waterlogging during certain parts of the year that can delay crop cultivation. Conversely, sediment causes groundwater levels to drop until there's not enough water to irrigate crops once the water has receded.

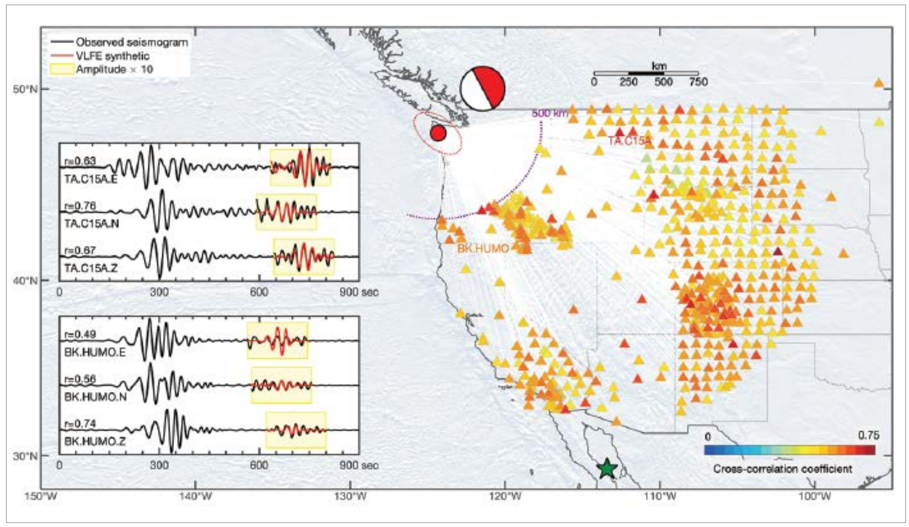
People have occasionally lost their homes when flash floods suddenly filled them with sand and gravel. One interviewee recounted a night when she heard a bang, and sediment, brought by a flash flood, suddenly filled more than half of her house. In recent years, sediment has also partially filled water bodies, reducing the degree to which they can store water and making subsequent flooding especially destructive.

Sediment deposition has even been associated with sexual harassment. When families have lost their homes and livelihoods, many men have gone to other districts in search of work. Some women reported that they experienced increased harassment from the men who remained behind.

The authors write that managing sediment will require creativity and coordination among the government, nongovernmental organizations, and people living in the haor. With climate change further stressing the region, developing a plan of action is a pressing need. (*Water Resources Research*, https://doi.org/10.1029/2021WR030241, 2022) **—Saima May Sidik,** *Science Writer*

Continent-Scale Detection of Triggered, Very Low Frequency Earthquakes

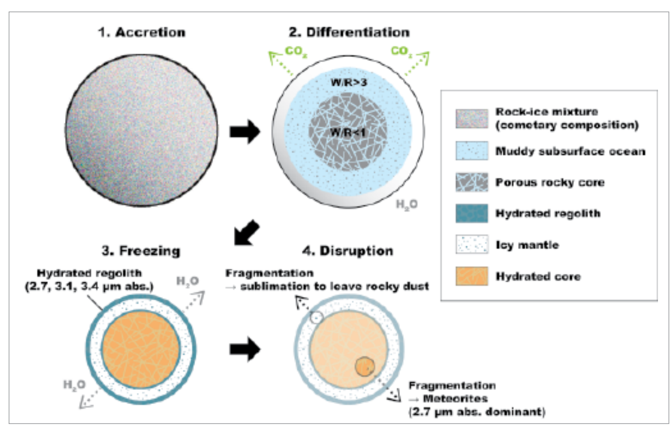
Enhanced geophysical networks have revealed a wide spectrum of fault slip behavior beyond simple seismic cycles over the past decades. One intriguing region in megathrust plate interfaces, including in the Cascadia margin of the northwestern United States, lies between the seismogenic zone and the deeper regions where phenomena such as nonvolcanic tremor occur. *Fan et al.* appear to have detected triggered, very low frequency events (VLFEs) in this gap, based on a comprehensive analysis of widespread seismometer recordings. The VLFEs detected included the largest event recorded globally so far. At magnitude 5.7, it was large enough to be seen in the longer-term crustal deformation recorded by strainmeters, making this also the first geodetic VLFE detection. While the physics of VLFEs and the gap zone remain to be clarified, these new observations provide important constraints on fault stress state and rupture dynamics, including for potential future earthquakes in Cascadia. (https://doi.org/10.1029/2021AV000607, 2022) **—Thorsten Becker**



Examples of observed and modeled seismic wave forms (insets) from an earthquake in 2009 (green star = epicenter) and a triggered, very low frequency event (VLFE; red circle) are shown here. Triangles denote seismic stations that recorded the events, with their color indicating the cross-correlation coefficient of the observed and modeled waveforms. The red and white circle indicates the focal mechanism of the VLFE. Credit: Fan et al.

A Deep-Space Origin for Volatile-Rich Asteroids

The origin of Earth's volatiles (e.g., water) is a perennial puzzle. Most likely they come primarily from volatile-rich (carbonaceous) meteorites, which are spectrally similar to volatile-rich asteroids in the main belt. But as *Kurokawa et al.* show, the similarity is not exact: Some of the main belt asteroids contain ammoniated clays, which are not seen in the meteorites. This is important because ammonia is not expected to be stable so close to the Sun. The authors propose that the volatile-rich asteroids formed at greater distances (>10 astronomical units) and were then scattered inward to the main belt. To explain the absence of ammoniated clays in meteorites, they posit a layered structure for the asteroids, with fragments from the more indurated, ammonia-free rocky cores expected to survive impact disruptions and atmospheric reentry as meteorites. This study bolsters other recent isotopic arguments that an outer solar system reservoir contributed significantly to Earth's growth. (https://doi.org/10.1029/2021AV000568, 2022) **—Francis Nimmo**



Steps in an envisaged scenario for the formation and evolution of carbonaceous asteroids include accretion (1), heating and differentiation (2) into a rock-rich interior and an icier exterior. The body then refreezes (3), with the inner and outer regions having different mineralogies and spectral absorptions. On impact disruption (4), fragments from the core preferentially survive to become meteorites. CO_2 = carbon dioxide; H_2O = water; μm abs. = micrometer absorption. Credit: Kurokawa et al.

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EPFL

Faculty position in Architectural Design and Heritage

at the Ecole polytechnique fédérale de Lausanne (EPFL)

EPFL's School of Architecture, Civil and Environmental Engineering (ENAC) invites applications for a faculty position in **Architectural Design and Heritage**. The position is open at the level of Assistant (tenure-track) or Associate Professor (tenured).

The Institute of Architecture and the City seeks a Professor of Architectural Design and Heritage to address the systemic challenges posed by the continuing climate crisis, rapid urbanization, and threats to eco-systems. Architecture must acquire an insightful understanding of its mission as transformed and transforming discipline with the ability and responsibility to bring up coherent, progressive and inclusive visions and solutions for our present, operating as socio-ecological catalyst within the ecological transition that is vital for life on earth.

We seek an architect of international status with a recognized intellectual footprint in heritage conservation, in light of sustainability concerns related to interventions on existing buildings, urban densification, adaptation of heritage buildings to contemporary standards in respect of historical typologies, coherent architectural expression and original construction technologies.

The successful candidate will have an outstanding record of professional experience in architectural design and heritage across scales, a proven capacity and interest for transdisciplinary approaches, and a strong commitment to excellence in teaching at the undergraduate and graduate levels.

We encourage applications from individuals with skills in critical analysis and professional evaluation of existing heritage as well as deep knowledge of historical construction methods, from the beginning of industrialization to modern times. Specifically, in addition to practical experience in architectural design and theoretical training in history of architecture, the applicant should have recognized contributions to conservative restoration, recovery and/or functional reconversion.

The Institute of Architecture and the City at ENAC, EPFL is an internationally leading institution in architecture, urban and territorial design, and home of one of the three university-level architecture schools in Switzerland. With its main campus located in Lausanne and its developing antennae in neighbouring cantons in Switzerland, EPFL is a growing and well-funded institution fostering excellence and diversity. It is well equipped with experimental and computational infrastructure, and offers a fertile environment for research collaborations between different disciplines. The EPFL environment is multilingual and multicultural, with English serving as a common interface. EPFL offers internationally competitive start-up resources, salaries and benefits.

The following documents are requested in PDF format: cover letter including a statement of motivation, curriculum vitae, publication list, statements of teaching interests and research vision (up to five pages each), and the names and addresses (including e-mail) of at least three (for the rank of Assistant Professor) or five (for the rank of Associate Professor) references who have already agreed to supply a letter upon request. Applications should be uploaded to the EPFL recruitment web site:

https://facultyrecruiting.epfl.ch/position/40599566

Formal evaluation of the applications will begin on **December 1st, 2022**.

Further enquiries should be made to:
Prof. Jeffrey Huang
Chair of the Search Committee
e-mail: SearchDesignHeritage@epfl.ch

For additional information on EPFL, please consult the websites: www.epfl.ch, enac.epfl.ch, ia.epfl.ch, sar.epfl.ch

EPFL is an equal opportunity employer and a family-friendly university that is committed to increasing the diversity of its faculty. It strongly encourages women to apply.

COLLEGE of CHARLESTON

TENURE-TRACK FACULTY, ASSISTANT OR ASSOCIATE PROFESSOR: MARINE GEOLOGY

The College of Charleston Department of Geology and Environmental Geosciences invites applicants with a Ph.D. in Geosciences or closely related field for a **tenure-track faculty position** to begin in **August of 2023**. We seek a faculty colleague able to teach courses in marine geology, seafloor mapping, introductory geology, and one or more courses in their field of specialty, and who is enthusiastic and qualified to mentor student experiential learning activities in marine geology. Candidates who can develop their own research program and secure external funds in areas such as marine geology, hydrography, and geoinformatics are strongly desired.

The Department of Geology and Environmental Geosciences has over 100 majors in Bachelor programs in Geology, Environmental Geosciences, and minors in Geology and Geoinformatics. The department is home to the successful BEAMS (Benthic Acoustic Mapping and Survey) program, a unique undergraduate-focused program with field experience, research activities, and coursework applicable to the Seafloor Mapping track in the Geoinformatics minor. We offer dozens of topical and interdisciplinary elective courses in the Geosciences, several of which serve students interested in marine geology. Many students have learned and trained in marine geology topics and conducted independent research, including over 100 of our students who have entered a career in marine geology. The Department also provides several courses and advises student research for the multidisciplinary Graduate Program in Environmental and Sustainability Studies, the M.Ed. in Science and Mathematics, an undergraduate major in Archaeology, and a minor in Environmental and Sustainability Studies. Collaborative opportunities are available with faculty in geochemistry, coastal and estuarine dynamics, environmental geology, geospatial sciences, paleoclimatology, paleoceanography, hydrology, paleontology, natural hazards, geophysics and seismology, volcanology, tectonics, and petrology. Our GIS and Remote Sensing laboratories are integrated with the Low Country Hazards Center in the School of Sciences and Mathematics Building. The department is also home to the Mace Brown Museum of Natural History, a public museum with world-class collections and facilities for specimen preparation, preservation, and display.

Applicants for this faculty position should submit the following materials:

1. Statement of Interest Letter
2. Curriculum Vitae
3. Teaching Philosophy
4. Research Program Statement
5. Unofficial Graduate Transcripts
6. Contact information for at least 3 references

Read the complete position description and apply at **https://jobs.cofc.edu/postings/12735**.

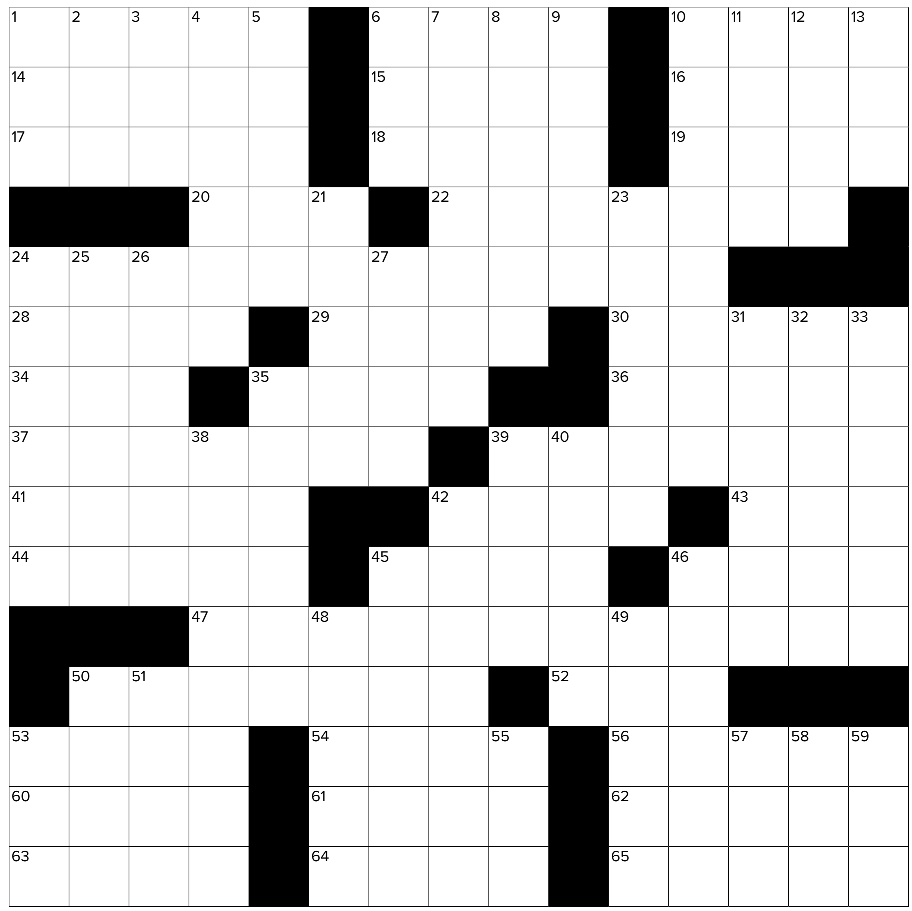
For more information about the department, visit **geology.cofc.edu**. Any questions should be directed to Timothy Callahan at **callahant@cofc.edu**. Applications will be reviewed beginning on **November 11, 2022** and the position will remain open until filled.

The College of Charleston is a comprehensive liberal arts and sciences university with a campus in downtown Charleston, SC; a marine campus at Fort Johnson close to downtown; and Stono Preserve, a 380-hectare rural campus 25 km southwest of downtown. The College of Charleston ranks in the top five of public universities in the South by U.S. News & World Report, and fourth among U.S. comprehensive universities in Study Abroad programming. We encourage applicants from traditionally underrepresented backgrounds to apply.

Science Fiction Futures

By Russ Colson, Minnesota State University Moorhead

This puzzle incudes two rebuses, in which multiple letters are entered into a single square.



ACROSS

1 Queued up, as in "what's _____ _____ for today?"
6 _____ Triple Junction, between the Nubian, Arabian, and Somali plates
10 Toy requiring a helmet, or a controversial mid-20th-century comic
14 Fictional flight pioneer ostracized for forward thinking, Jonathan _____
15 Prim, Pete, or Tokyo
16 Copied
17 Pioneer in electrical engineering
18 Formerly
19 Tear
20 Nation on the eastern Mediterranean (abbr.)
22 Where a terrestrial planet meets its atmosphere
24 Often gneiss or granite
28 "If men could see _____ _____ we really are, they would be…amazed." —Charlotte Brontë
29 Monkey puzzle or baobab
30 Commercial accounts record
34 Advanced deg. in religion
35 Prevaricator
36 Stories à la King?
37 Several collies in movies, TV, and books
39 Launch
41 Project feeling
42 _____ of the Pioneers
43 River, province, or city in Russia, or a geological ending for t-
44 Of the kidneys
45 Not this
46 "On _____," a type of work for an optimist
47 Like oil or coal, for example
50 Fully natural insulative fabric, or "_____ _____ and a yard wide"
52 Original designation for the Apollo Moon-orbit transfer vehicle
53 Subtropical succulent
54 Not even a zero
56 *Le Petit Prince* or *Discours de la Méthode,* for example, or an old French coin
60 Pass, as in "as the days _____ _____"
61 Molding pattern, as a Roman _____
62 Title word in a SF novel prognosticating deep marine exploration
63 Indigenous Peoples of the Great Basin
64 Timid people, or games played with coconuts at fairs
65 How one followed their dreams?

DOWN

1 East in Berlin
2 Born
3 Social media marketing appeal, as in "_____ _____ on Instagram," or a major river in Spain
4 Those joined in a common purpose
5 Cyto or proto
6 Were, when it all started
7 1909 SF prognosticator of technology-driven isolation in *The Machine Stops* E. M. _____, or a name derived from one who takes care of trees
8 Allay doubt
9 Rocket or decor
10 Long-tailed parrot
11 Grp. of oil-producing nations
12 SF prognosticator of an egalitarian future _____ Roddenberry, or a bit of organic data?
13 It seems _____ that they are called _____ even though they make up half their group population
21 Knot again?
23 Bass symbols are often _____
24 SF prognosticator of the importance of diversity and change to counter hierarchical thinking Octavia _____, or a hierarchical servant
25 Humiliate, meaning the same with its first letter removed
26 Strong man
27 The _____ lobbying efforts often center on the Second Amendment
31 Second collection?
32 Tower
33 Frontal do-over
35 Avoid attention
38 Chemist Miller and filmmaker Kubrick
39 Type of shark or officer
40 Spy info
42 SF prognosticator of the ethical risks of technological advancement Mary _____, or a molluscan diminutive?
45 In ripples, a partner to ridge
46 Sandy desert wind of North Africa, or an alternate spelling for the last Hebrew judge
48 Naughty actions
49 SF prognosticator of temporal advancement H.G. _____, or water extractors?
50 Gobs and gobs
51 Ear or lava
53 Geoscience org. that leads the future—and a hint for two crowded rebus squares in this puzzle
55 *Miz* or *Misérables*
57 Like this puzzle clue?
58 Workout count unit
59 East in Paris

See p. 63 for the answer key.