Eos

VOL. 102 | NO. 11
NOV–DEC 2021

SCIENCE NEWS BY AGU

SCIENCE *is* SOCIETY

Shared insight is how communities discover real solutions

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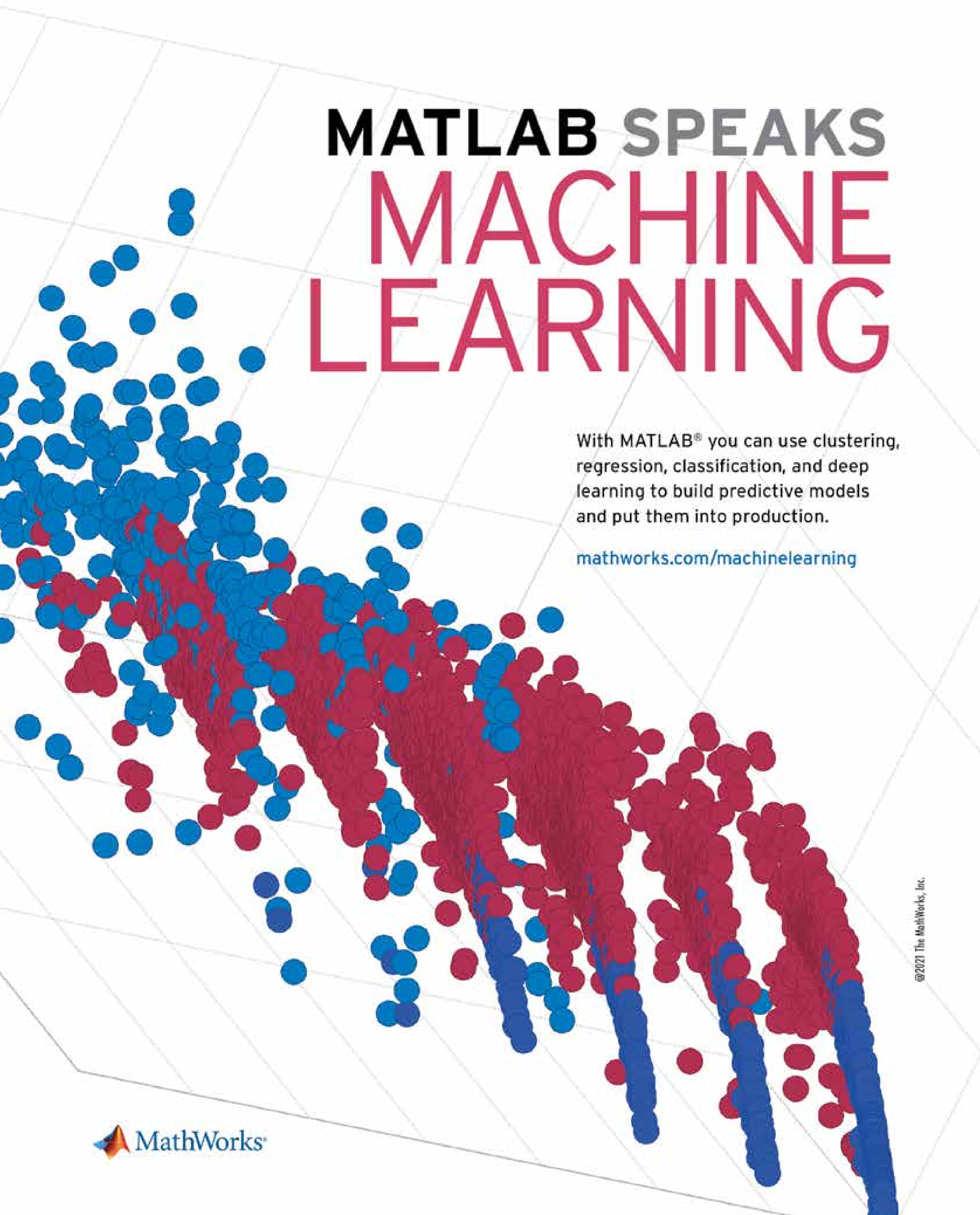
ADVANCING EARTH AND SPACE SCIENCE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Knowledge Brings Us Together

This special double issue of *Eos* is, at its heart, what we strive to make every issue about: Illustrating the concept that to answer all of our questions—from "how do we understand this incredibly specific Earth process?" to "how do we change the trajectory of our planet's climate system?"—we have to work together with the best available knowledge. "Science Is Society" is the theme of AGU's Fall Meeting 2021 and this issue is dedicated to the scientists gathering in New Orleans and online everywhere in December.

"When societal responses are based in science, society benefits through lives saved, fewer severe disease incidences, and a quicker economic recovery; when we ignore science, hospital beds fill up, families are torn apart, and the economy suffers," said Christine Kirchhoff at the University of Connecticut. Kirchhoff, *Eos*'s science adviser representing AGU's Science and Society section, consulted on this issue.

Climate change; pollution of land, water, and air; and myriad other global challenges necessitate good science-based decisionmaking. Scientists need to remember that "we make better decisions and better science in partnership with society," Kirchhoff said.

One excellent example of this partnership is happening in Washington, D.C. Residents armed with science pushed city managers to embark on a $2.7 billion infrastructure project to curtail sewage overflow into the Potomac and Anacostia rivers. "This article really captures the strength of the interplay between policy, science, and collaborations between government, nongovernment, and community science efforts to make progress on water quality," said Kirchhoff. "We need the aspirations of the Clean Water Act—with its levers of enforcement and accountability—to enable action to clean up our rivers, and when action lags, this reporting shows how good science and the leadership of concerned residents combine to hold cities accountable." Read the story on page 64.

An enormous part of getting the best available science is making sure the collection of data is not done from a single viewpoint. The international hydrologists in the feature article on page 44 show how they integrate Western scientific practices with Indigenous Knowledges to serve their home communities and to lift up our collective knowledge of the world.

You'll find so much more in this issue on science and society partnerships, from how geoscientists are overcoming the physical challenges of ocean terrain just off U.S. coastlines to increase offshore wind energy, to relatively simple ways for scientists to engage in outreach via their field research, and even how we might want to think about protecting our Moon as we teeter on the edge of being a society with real off-world industry.

Finally, just for fun, we're taking you on a voyage inside Mars. Thanks to NASA's InSight mission, which placed a seismometer on the Red Planet, scientists now have an exciting new view of Mars's interior. Enjoy our special poster "Mars from the InSight Out" inside this issue, or download it from bit.ly/Eos-Mars-poster.

As the importance of the topics covered in this issue grows, Kirchhoff's section has been reimaging its purpose. Science and Society is the new name the group adopted last year, said Julie Vano of the Aspen Global Change Institute and the section's president, so its members could "better connect with society by creating a welcoming community for those whose scholarship includes science policy, community science, science communication, social and behavioral sciences, and art and science." We hope you'll explore more about their section during #AGU21 and think more about the ways in which making partnerships that connect your research to society benefits you, your research, and us all.

Heather Goss, Editor in Chief

Eos

AGU ADVANCING EARTH AND SPACE SCIENCE

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

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

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Randy Fiser, Executive Director/CEO

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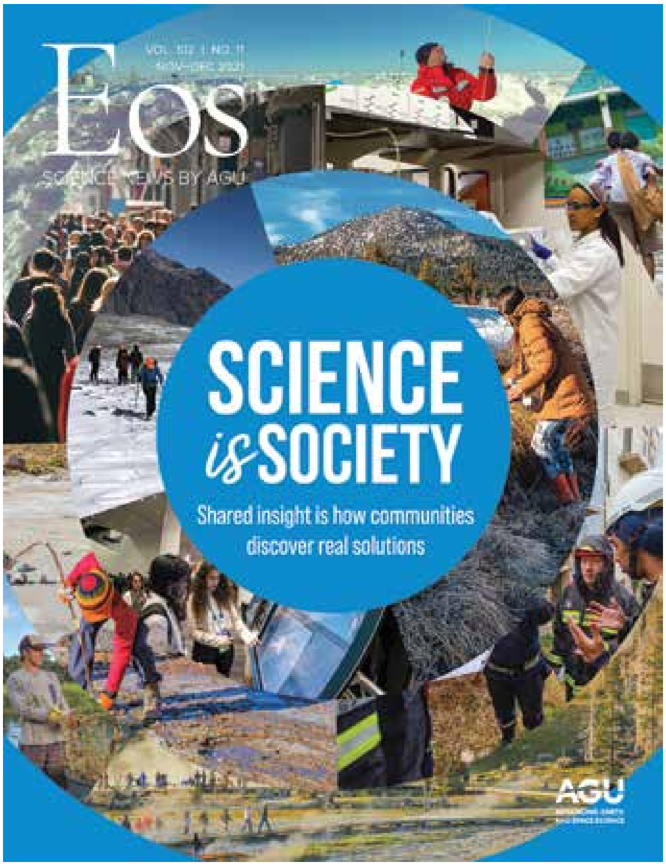

On the Cover

Design by Beth Bagley. Clockwise from top: A researcher on the MOSAiC expedition in the Arctic Ocean (Byrd Polar and Climate Research Center); Students in Ayuthaya, Thailand, walk in a flooded street (Pentium5/DepositPhotos); Visitors watch Grand Geyser in Yellowstone National Park (Jim Peaco, National Park Service); Vance Farrant in Waiale‘e, Hawaii (Nick Farrant); A crowded street in Istanbul (iStock .com/filadendron); A technician at the Cancer Genomics Research Laboratory (National Cancer Institute/Unsplash); A training for earthquake relief workers (ThisisEngineering RAEng/Unsplash); Carolina Muñoz-Saez studies the El Tatio geyser in Chile (Max Rudolph, University of California, Davis); Glaciologists traverse a valley glacier in Chile (Alfonso Fernández); Helen Fillmore conducts water quality monitoring in Hope Valley, Calif. (Mo Loden, Alpine Watershed Group); Attendees at AGU’s Fall Meeting 2019 (Event Photography of North America Corporation)

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Prince Sultan Bin Abdulaziz International Prize for Water

Recognizing Innovation

Winners for the 9th Award (2020)

Creativity Prize

1) The team of Dr. Benjamin S. Hsiao (Stony Brook University, New York, USA)
for the development of adsorbents, coagulants and membrane materials from sustainable, biomass-sourced nanocellulose fibres along with numerous practical applications that promise to provide effective water purification for off-grid communities of the developing world. (The team also includes Dr. Priyanka Sharma, research scientist at Stony Brook University).

Dr. Benjamin S. Hsiao

2) The team of Dr. Sherif El-Safty (National Institute for Materials Science, Japan)
for developing novel nano-materials in hierarchal and micrometric monoliths to achieve a nano-filtration/capture/detection process that quantitatively detects and selectively removes a wide range of water contaminants in a single step. A diverse range of these materials, which are conducive to mass-scale production, provides nano-filtration membranes and filters for water management applications, including purification, remediation, and the monitoring of hazard levels of various water sources.

Dr. Sherif El-Safty

Surface Water Prize

Dr. Zbigniew Kundzewicz (Polish Academy of Sciences, Poznan)
for advancing our understanding of the relationship between flood risk, river flow, and climate change.

Dr. Zbigniew Kundzewicz

Groundwater Prize

Dr. J. Jaime Gómez-Hernández (Universitat Politècnica de València, Spain)
for pioneering work on solving the "inverse problem" in hydrogeology.

Dr. J. Jaime Gómez-Hernández

Alternative Water Resources Prize

Dr. Peng Wang (King Abdullah University of Science and Technology, Thuwal, Saudi Arabia)
for work at the forefront of solar-evaporation water production technology.

Dr. Peng Wang

Water Management and Protection Prize

Dr. Jay R. Lund (University of California Davis, USA)
for the development of the CALVIN water supply optimization model that couples traditional water-supply criteria with economic considerations.

Dr. Jay R. Lund

Nominations are open for the 10th Award. Nominations can be made online until 31 December 2021.

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Ancient Flint Tools Reveal Earth's Changing Magnetic Field

Although we rarely stop to consider it, Earth's magnetic field is an important part of our daily lives. The magnetic field protects our planet from charged particles emitted by the Sun; high doses of these particles can cause malfunctions in the electrical grid and in satellites.

But thanks to complex processes unfolding deep within Earth, the magnetic field is always changing. To predict what it might do in the future, scientists are looking deep into its past.

This is no easy task—intentionally kept human records of the magnetic field exist for only the past few hundred years. To see further back in time, scientists rely on "accidental" records and on volcanic and sedimentary rocks, said Lisa Tauxe, a geophysicist at the Scripps Institution of Oceanography. Tauxe is a coauthor of a new study that used ancient artifacts to analyze changes in Earth's magnetic field thousands of years ago—as far back as 7600 BCE (bit.ly/ancient-artifacts). The study was published in the *Proceedings of the National Academy of Sciences of the United States of America.*

Heated flint dates back much further than pottery, likely to around 50,000 years ago, so it could potentially substantially increase our understanding of the magnetic field's past.

These accidental records, Tauxe explained, can be created when certain materials are heated to very high temperatures. When they cool, magnetic minerals within the material are frozen in place, providing a snapshot of the direction and strength of Earth's magnetic field at the time.

Clues from the Past

Ancient pottery is a robust and widely used way to study the history of Earth's magnetic field. But in the context of geologic history, pottery poses a problem for researchers who want to delve deeper into the past. That's where the present study comes in.

Scientists analyzed pottery fragments and burnt flints from Wadi Fidan, Jordan, to determine the history of Earth's magnetic field. Credit: Thomas E. Levy

"In this study, what we did was to try to push the record back beyond pottery," said Tauxe.

These researchers wanted to see whether they could obtain information about the magnetic field from flint, one of the most common materials used to make stone tools. It is thought that ancient humans deliberately heated the flint to make it easier to work with, said study coauthor Anita Di Chiara, a paleomagnetist at Scripps and at Italy's National Institute of Geophysics and Volcanology.

Heated flint dates back much further than pottery, likely to around 50,000 years ago, so it could potentially increase our understanding of the magnetic field's past by a substantial amount. Di Chiara said that obtaining data from flint is difficult because it is generally not very magnetic. However, in this study, the researchers were able to obtain data from tiny impurities in the flints.

Using artifacts from Jordan, including both flint and pottery, researchers found that the magnetic field around 7600 BCE was only two thirds the strength of today's field but just 600 years later had greater strength than today's field. Then, around 5200 BCE, it weakened again.

Today, said Tauxe, the strength of Earth's magnetic field is dropping very quickly. Although this change isn't necessarily catastrophic, Tauxe said it could cause problems for some types of technology. "Our electrical grid and satellites will become more vulnerable to solar storms.... We need to build our infrastructure with that in mind—that we're losing the protection of the magnetic field."

Although Tauxe said the overall strength of the field won't be very low for another 500 or so years, she noted that one region of the world, an area over parts of South America and the South Atlantic Ocean, is already experiencing an unusually weak magnetic field. This weak spot, called the South Atlantic Anomaly, can leave satellites vulnerable to charged particles, which can cause glitches and malfunctions.

Early Humans

Studying the magnetism of ancient objects is important for understanding the magnetic field's history and could also help us understand human history. Erella Hovers, a professor of prehistoric archaeology at the Hebrew University of Jerusalem, said that studying the magnetism of ancient artifacts can be very useful in an archaeological context. Such study can help archaeologists determine the relative ages of ancient human-made objects. This method is especially useful for objects that are beyond the scope of carbon dating, which is effective only for things that are less than 50,000 years old.

For example, she said, archaeomagnetism allows scientists at older sites to "see if the features [they're] studying were created at one particular point in time, which would suggest something about the rapidity of the site being formed, or whether it's just a big hodgepodge of things that were mixed in place and were originally formed in different periods."

Both Tauxe and Di Chiara emphasized the collaborative nature of this work and noted the importance of partnerships between geophysicists and archaeologists in learning more about Earth's magnetic history.

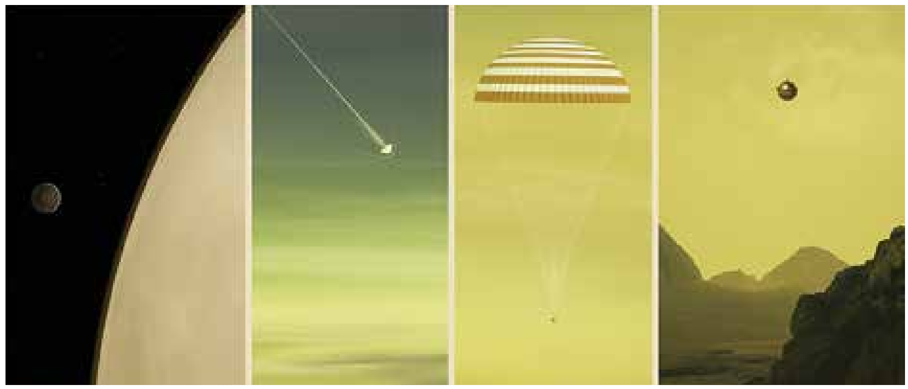
By **Hannah Thomasy** (@HannahThomasy), Science Writer

Mission to Venus Could Help Solve an Atmospheric Mystery

Floating along Venus's thick atmosphere are shadowy patches, morphing in shape and size, like huge algal blooms. Scientists first photographed these atmospheric features in 1927, and some researchers have suggested that these so-called unknown absorbers could be signs of life.

"For all we know [they] could be bacteria," said Sanjay Limaye, a planetary scientist at the University of Wisconsin–Madison. "Could there be life in the clouds?"

Although scientists have their hypotheses, no one has confirmed what is causing the dark areas in the atmosphere. NASA's new mission to Venus, DAVINCI+ (Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging), may bring scientists closer to an answer. (NASA is in the process of changing the mission name from DAVINCI+ to DAVINCI.)



DAVINCI+, one of NASA's latest missions to Venus, will study the planet from above and within. Credit: NASA GSFC visualization and CI Labs/Michael Lentz and colleagues

DAVINCI+ Answers the Call

The mission, announced in June, will drop a probe into Venus's clouds—a beach ball–sized titanium sphere that will dive through the atmosphere and, for more than an hour, collect data while falling about 70 kilometers (43.5 miles). This mission, scheduled to launch between 2028 and 2030, will be the first time a spacecraft will probe the planet's atmosphere in situ since 1985, when the Soviet Union's Vega 2 spacecraft investigated the planet's atmosphere.

> **"Could there be life in the clouds?"**

DAVINCI+ isn't designed to detect life. "We're still trying to get the right measurements to simply ask the right questions," said Jim Garvin, DAVINCI+'s principal investigator. But among the mission's other scientific goals, researchers hope it will help solve the mystery of these atmospheric patches and, more broadly, provide a deeper understanding of the atmosphere, which is crucial for determining Venus's habitability.

An Old, Unanswered Question

Is there life on Venus? Because Venus has many similarities to Earth—such as size and interior composition—many scientists once thought Venus could be an oasis for life. But when spacecraft began exploring the planet in the 1960s, they uncovered an inhospitable surface environment with temperatures hot enough to melt lead and a thick carbon dioxide atmosphere with crushing average pressures 92 times those at Earth's sea level and surface.

Then in 1967, Harold Morowitz and Carl Sagan proposed that although life can't survive on the surface, some microbes may survive in the clouds. Early Venus missions found evidence of water vapor in the atmosphere. In the cloud layers roughly 50 kilometers (30 miles) above the planet's surface, atmospheric pressures are comparable to those at Earth's sea level, and temperatures range between 100°C (212°F) and 60°C (140°F)—much cooler and more hospitable than the surface. On Earth, for instance, some organisms—such as microbes in hydrothermal vents—can survive in temperatures as high as 121°C (249.8°F).

In addition, the patches are created when something, perhaps microbes or some biological process, absorbs primarily ultraviolet light from the Sun amounting to about half the Sun's energy that reaches Venus, according to Limaye. In 2018, Limaye and his colleagues found that the patches absorbed light at many of the same wavelengths as some terrestrial bacteria and biological molecules, such as proteins.

> **"We're still trying to get the right measurements to simply ask the right questions."**

Using DAVINCI+ to Get One Step Closer

The unknown absorbers, of course, could be nonbiological. Scientists have already detected some sulfur-bearing compounds in Venus's atmosphere that absorb at least some of the ultraviolet light, and other similar chemical species might be the main cause of the dark patches, Garvin said. DAVINCI+ will try to help determine the chemistry that's producing the bulk of these dark patches and perhaps point sci-

▶ Read the latest news at **Eos.org**

entists toward a biological or nonbiological origin.

During two flybys before it releases the probe, the DAVINCI+ carrier spacecraft will try to identify the absorbers using a high-resolution ultraviolet spectrometer. An ultraviolet camera will also take videos of the clouds at high resolution and study how the dark patches move.

“It is a great time to be interested in Venus… We’re going to learn spectacular stuff.”

If life does exist in the clouds, it likely would have originated the same way it did on Earth: in an ocean. Some computer models of Venus’s ancient climate suggest that it did once have a shallow ocean, chemical traces of which might still exist in its atmosphere. An onboard mass spectrometer will measure hydrogen and its chemical sibling deuterium to reveal how much water Venus’s surface has lost throughout history. The probe’s laser spectrometer will not only help identify what’s absorbing ultraviolet light but also measure chemicals important for determining habitability, such as sulfuric acid, water, and chemical nutrients.

Compared to the instruments that last visited Venus decades ago, the spectrometers “are an order of magnitude higher in resolution [and] precision,” Garvin said.

DAVINCI+ won’t be alone at Venus. In the next decade, NASA, the European Space Agency, and the Indian Space Research Organisation will send three more spacecraft—VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy), EnVision, and a to-be-named orbiter—to the planet, beginning a new era of Venus exploration. “It is a great time to be interested in Venus,” Garvin said. “We’re going to learn spectacular stuff.”

By **Jaime Cordova** (@jaimecor_94), Science Writer

This article was produced with support from the National Association of Science Writers’ David Perlman Virtual Mentoring Program.

When Rivers Are Contaminated, Floods Are Only the First Problem

Dioxins—the category of chemicals that includes Agent Orange—have been banned in the United States since 1979. But that doesn’t mean they’re gone. Dioxins and other banned chemicals are buried just beneath the surface waiting to be unearthed.

A new perspective paper published in *Journal of Hazardous Materials* calls attention to an understudied area: the remobilization of pollutants buried in riverbeds (bit.ly/riverbed-pollutants). Chemicals have a knack for binding to sediments, meaning that chemical spills in rivers frequently seep into sediments instead of flowing downstream. Future layers of silt bury the pollutants and hide the problem.

But persistent chemicals in riverbeds are “ticking time bombs,” warned Sarah Crawford, an environmental toxicologist at Goethe University Frankfurt and lead author of the paper. The buried chemicals can easily be remobilized. “It just takes one flood event,” she said.

Little Pockets of Pollution

The paper comes from an interdisciplinary research team based mostly in Germany, a country that faced catastrophic floods this year that defied comparison. As the climate warms, similarly intense storms are expected to increase. Floods cause immediate turmoil, but chemical remobilization can prolong the disaster.

“Cohesive sediments are really stable over long ranges of flow velocities, but at some point the sediment bed just fails,” said Markus Brinkmann, an ecotoxicologist at the University of Saskatchewan and a coauthor of the paper.

“Little pockets of contamination are really easily dispersed by flood events.”

When the riverbed fails, the turbulent water fills with sediment. That churning water can spread toxins widely. After Germany’s Elbe river flooded in 2002, for example, hexachlorocyclohexane concentrations in fish were 20 times higher than they were

Hurricane Harvey flooded or damaged at least 13 Superfund sites in 2017, sending cancer-causing compounds into Texas waterways. Credit: S.Sgt. Daniel J. Martinez, U.S. Air National Guard before the floods. In another example from 2017, Hurricane Harvey flooded or damaged at least 13 Superfund sites in the United States and sent cancer-causing compounds flowing into Galveston Bay in Texas.

"Little pockets of contamination are really easily dispersed by flood events," Brinkmann said.

The locations of these little pockets are uncertain, complicating the problem. Urban areas and agricultural hot spots are obvious starting points for research and remediation, "but we just can't pinpoint all of them," said Crawford. "Maybe a farmer in the '60s was spraying DDT. We don't have records of that."

Other questions remain unanswered. How bioavailable are reintroduced chemicals? How toxic are chemicals after decades bound to sediments? What is the economic risk of inaction? "A lot of this hasn't been studied," noted Crawford.

The recent paper doesn't attempt to answer questions about the presence and release of riverbed toxins but tries, rather, to spur interdisciplinary research on the growing threat.

Involving the Community

Interdisciplinary research is essential for such a complex problem. As evidence, the paper's 16 authors include a mix of toxicologists, economists, microbiologists, chemists, and engineers.

But it's important that the research expands beyond academia, too. "To really accomplish this, particularly at the scale [at which] it needs to be done, you can't have grad students collect every sample," said Ashaki Rouff, an environmental geochemist at Rutgers University–Newark who was not involved in the research. "You really need to engage the public."

"To really accomplish this…you can't have grad students collect every sample. You really need to engage the public."

That often means collaborating with marginalized communities. "Issues of climate change and contamination and pollution disproportionately affect communities of color and low-income communities," Rouff added. Getting residents involved in the research "is a way to empower those vulnerable communities and get them more agency in the environmental health of their community."

"It's really important to work with community-based organizations for this type of work, especially in these types of marginalized communities," agreed Vanessa Parks, an associate sociologist with the RAND Corporation who was not involved in the research. Residents of at-risk regions are well aware of the threat next door; excluding them from the conversation can increase the frustration and psychological burden of living near a contaminated site.

"Working with communities and having open dialogue about the risks and about environmental monitoring can help engender trust," Parks said.

Ticking Time Bombs Get Louder

While the paper was a call for transdisciplinary action, Crawford and Brinkmann and their colleagues have already facilitated a research network to address the issue. They brought together at RWTH Aachen University in Germany graduate students from multiple disciplines (engineering, economics, ecotoxicology, and more) to research different angles of flood risk and contaminant mobilization. They published an open-access article on their efforts in 2017 (bit.ly/project-house-water).

"I really hope to move forward working in an interdisciplinary manner," said Crawford. "I hope we train this next generation of scientists to be able to communicate across different disciplines."

It takes only one fast moving flood to rip up buried toxins and contaminate an entire area. As the climate warms and storms intensify, the ticking time bombs of polluted river sediments are only getting louder.

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

icdp

The International Continental Scientific Drilling Program (ICDP)

Call for Proposals

The International Continental Scientific Drilling Program, ICDP coordinates and supports multinational endeavours in continental scientific drilling. The program focuses on themes of global geoscientific importance underpinning socio-economic challenges, including geodynamic processes, geohazards, georesources and environmental change, as outlined in the ICDP Science Plan (**www.icdp-online.org/media/icdp-science-plan**).

With this announcement, the ICDP invites Earth scientists to submit pre-proposals, workshop proposals and full proposals in which drilling is required to achieve critical research goals. This call is open to investigators from ICDP member countries (Austria, Belgium, China, Czech Republic, Finland, France, Germany, Iceland, India, Israel, Italy, Japan, New Zealand, Norway, South Africa, Spain, Sweden, Switzerland, The Netherlands, United Kingdom, and United States of America) as well as from countries considering membership in the ICDP.

As recently introduced, the ICDP invites proposals in cooperation with the International Ocean Discovery Program, in which coordinated drilling on land and at sea is required. These Land-To-Sea project proposals (L2S) are to be submitted first as Preliminary Proposals to ICDP.

Detailed information on the scope of the ICDP, submission guidelines for proposals, proposal format, the process for developing a successful proposal, the grant conditions and the evaluation process is available at: **www.icdp-online.org/proposals**. Land-To-Sea proposals will be jointly assessed with IODP review panels.

In the proposal evaluation process ICDP will primarily consider scientific quality and global relevance. Furthermore, also technical and financial aspects as well as equality, gender and contribution of early career scientists will be taken into consideration.

For full proposals successfully evaluated by the ICDP panels, ICDP provides operational support and allocates partial funding for drilling-related costs, while matching funds will need to be acquired by the project PIs from national and/or international funding bodies. This concept of commingled funding and international cost sharing, in combination with knowledge and technology transfer, has proven very successful and positive reviews from ICDP typically serve as door-opener to successfully allocate matching funds from funding agencies.

The deadline for submission of all proposals is **January 15, 2022**. Please submit a single file of less than 10 MB size **using the new proposal cover sheet** according to the guidelines via e-mail to the ICDP Program Office using: **proposal.submission@icdp-online.org**.

Better Together: Perovskites Boost Silicon Solar Cell Efficiency

For decades, traditional silicon-based photovoltaic cells have been the industry standard for converting sunlight into electricity—but as a photon-absorbing material, silicon is not actually all that efficient. On average, solar panels made with crystalline silicon convert between 18% and 22% of the Sun's energy into usable electricity, with an upward potential limit of 33%. Despite this limitation, crystalline silicon photovoltaic cells account for 95% of the solar cell market.

By layering traditional silicon cells with a mineral called perovskite, however, materials scientists are engineering tandem solar cells that significantly boost efficiency, without derailing well-established silicon cell manufacturing pathways.

"Tandem solar cells have significantly higher energy-conversion efficiency than today's state-of-the-art solar cells. Thus, tandem cells can contribute to lowering the cost of solar energy, in particular in rooftop solar systems, where high efficiency is of central importance," Dirk Weiss, a materials scientist with First Solar, recently wrote in *Joule* (bit.ly/tandem-solar). "A new generation of low-cost tandem cells is needed to enable widespread implementation. Hybrid-perovskite top cells combined with silicon bottom cells are currently the most popular low-cost tandem candidate under development."

In a new perspective published by *Applied Physics Letters,* a team at Oxford PV in the United Kingdom led by Laura Miranda Pérez, head of materials research, and Chris Case, the chief technology officer, presents a case for commercializing tandem solar cells by combining existing silicon cell technology with synthetic variants of the perovskite (bit.ly/tandem-perovskite).

Perovskite-silicon solar cells set a record solar cell efficiency of nearly 30%. Credit: Oxford PV

The mineral perovskite, also known as calcium titanate, was discovered in the Ural Mountains in 1839, but the perovskite used in solar cells is synthesized in a lab from readily available components. These perovskite solar materials can be applied in very thin layers, making them an ideal material to add to existing silicon cell manufacturing processes.

"Perovskites are the perfect partner for a tandem system with silicon," said Miranda Pérez.

By adding perovskite, which more efficiently captures the blue region of the solar spectrum, to silicon, which targets the red region, Oxford PV has set a record solar cell efficiency of more than 29.5%. With further development, efficiencies could reach as high as 39%, said Miranda Pérez. Other research teams have demonstrated that photovoltaic cells made with only perovskite and no silicon are also viable, but these solar cells cannot exceed the practical efficacy of any single solar cell, which is around 26%. The multijunction, or tandem, approach of Oxford PV is the best way to break the 26% practical efficiency barrier, said Miranda Pérez.

"Of all the alternative solar cell technologies, silicon-perovskite tandem cells are proving to be the most promising because they offer a degree of tunability that you don't have with a lot of the competing technologies," said Joseph Berry, a senior research scientist at the National Renewable Energy Laboratory in Golden, Colo., who was not involved in the new study. "This new perspective does a great job of showing how perovskites can enhance and advance silicon technologies without interrupting manufacturing."

Scaling Sustainably

Oxford PV, a company cofounded in 2010 by University of Oxford physicist Henry Snaith, has focused on developing perovskite-on-silicon tandem cells since 2014. Initially, ensuring the long-term stability of perovskite was the principal challenge, but current perovskite-on-silicon tandem cells have passed key accelerated stress tests for solar cells, known as the IEC 61215, established by the International Electrotechnical Commission. The tandem cells are expected to meet or exceed the industry expectation of 25 or more years of durability in the field.

The team's next step is to ramp up production at Oxford PV's factory in Brandenburg, Germany, which houses the world's first perovskite-on-silicon production line, with a capacity of 100 megawatts. "The line build-out has been completed, and we will be taking tandem cells into the market next year," Miranda Pérez said.

Initially, the company's solar cells will be made available for residential rooftops, where space is at a premium. With additional production capacity, Oxford PV has set its eyes on commercial rooftops and utility-scale applications. "As a company we are very concerned about the climate crisis, and the best way we can play our part is to deploy this technology as quickly as we can," said Miranda Pérez.

"Perovskites can enhance and advance silicon technologies without interrupting manufacturing."

As countries commit to reducing emissions to meet United Nations climate goals by 2050, solar power is projected to become more pervasive. "I think tandem technologies will be requisite to hit future solar and climate goals," Berry said.

"We want to help people understand the huge potential of perovskite-on-silicon tandem technology to boost the efficiency of solar installations and to help the world reach the goal of providing sustainable energy for all," said Miranda Pérez.

By **Mary Caperton Morton** (@theblondecoyote), Science Writer

Building a Better River Delta

Natural wetlands like the Mississippi delta provide inland areas with protection from floods. Credit: Andrew Moodie

The Mississippi River delta is sinking, its coastal wetlands are disappearing, and its coastal marshes are drowning. The delta has been aggressively engineered for about 200 years, with the building of diversions (like levees or alternate channel paths) to control the flow of water. As with many deltas, those diversions are often built near the coast. But a novel approach has identified a better location: cities.

The strategies behind most river diversions are driven by economic concerns and "really ignore the natural process of the river to want to avulse at a specific place with some average frequency," said Andrew Moodie, a postdoctoral researcher at the University of Texas at Austin. The process of avulsion, in which a river jumps its banks to flow on a steeper slope, is crucial to flooding and river dynamics. But diversions notwithstanding, that water will eventually go where it wants to, which can result in flooding, loss of homes and businesses, and even loss of life.

Moodie and his colleagues' new research, published in the *Proceedings of the National Academy of Sciences of the United States of America,* describes a new framework for selecting the optimal placement for river diversions (bit.ly/river-diversions). "Because of the interaction between the river wanting to do what rivers do and a society that wants to minimize damage to itself, there emerges a best location that does both of those things," said Moodie. "It lets the river do the closest to what it wants to do, but it also minimizes the damage to the society."

"It's actually easier to justify more expensive projects because you have to protect this infrastructure now or you lose so many more benefits from it."

Downtown Diversions

Moodie's framework combines two models. The first simulates river and sediment movement scenarios to predict the timing of avulsions; the second estimates the societal benefits of diversions by factoring in the cost of flood damage and the costs of diversion engineering, like buying land and construction, as well as annual revenues (from agriculture, e.g.).

Moodie's framework points to urban areas as often better locations for river diversions than the rural and suburban areas where most river diversions are constructed. This finding counters a prevailing theory that cities are less sustainable and may have to be abandoned as seas continue to rise. Placing diversions closer to cities makes economic sense because losses from flooded farmland may last a season, but floods in urban areas can cause longer-term damage. "It's actually easier to justify more expensive projects because you have to protect this infrastructure now or you lose so many more benefits from it," he said.

The biggest challenge to implementing a new river diversion framework is involving different parties and their needs, which are diverse and sometimes conflicting. Shareholders include rural, suburban, and urban residents and landowners; agricultural businesses; water engineers; municipal, state, and regional governments; environmental organizations; and local community leaders.

"River management has a complex history that we're trying to fit into," Moodie said. "We are geomorphologists, we're scientists, but we recognize and want to stress the importance of contextualizing our work within the societies that it matters to."

Jaap Nienhuis, an associate professor of geosciences at Utrecht University in the Netherlands who was not involved in the new research, said the study is elegant and novel. "It's one of the first papers that tries to couple human action and also landscape dynamics for river deltas," he said.

The framework could help river engineers and others responsible for river management by offering a discrete set of parameters, said Nienhuis. "It gives people an overview of things to consider without it getting out of hand in terms of the things you need to worry about."

Sea Level Rise

Flooding is not, of course, a problem limited to the Mississippi delta; it's happening around the world because of sea level rise, storm surge increases, and human interven-

The Mississippi River delta has been engineered for hundreds of years and is sinking—but a new approach to river diversions outlined by Andrew Moodie (pictured) could help protect it. Credit: Andrew Moodie

tions, like seawalls, which can make the problems worse.

While land subsides, climate change is contributing to sea level rise. Climate change is also contributing to more frequent and violent coastal storms. Infrastructure like dams and levees protects communities from floods but interrupts sediment flow, which deltas need to form natural wetlands that protect inland regions.

"By protecting us from floods, we've also eliminated any natural land area gain or elevation gain in deltas," Nienhuis said. "So we're definitely trying to shift the focus to how we can have diversions, for example, that would make deltas gain some land and be more resilient against sea level rise."

Sea level rise itself is a variable Nienhuis would like to see incorporated into Moodie's framework. The current models "keep sea level constant, and [researchers] let the delta grow," he said. "It would be interesting and I think a relatively straightforward follow-up to have sea level rise and see what that does to these findings."

By **Danielle Beurteaux** (@daniellebeurt), Science Writer

Lake Erie Sediments: All Dredged Up with Nowhere to Grow

In 2014, a Lake Erie algal bloom sent a cloud of toxins into Toledo, Ohio's water supply, forcing the city to shut down water service to 400,000 residents. Like many lakes in agricultural areas, Lake Erie produces thick, smelly algae mats when the water gets warm. Temperatures above 60°F can trigger algal blooms, and Lake Erie—shallowest and warmest of the Great Lakes—hit nearly 80°F in 2020. In addition, the lake is the final destination for fertilizers washing off of area farms—that's a recipe for excess photosynthesis.

"You're cooking a perfect soup for having a very productive lake," said Angélica Vázquez-Ortega, an assistant professor of geochemistry at Bowling Green State University.

Whereas fertilizers are a source of Lake Erie's annual algae issue, research from Vázquez-Ortega's lab suggested that agriculture could be a partial solution, too. Instead of applying more fertilizers upstream, farmers could remove nutrients from the lake by mixing Lake Erie sediment into their soils. The research is especially timely as a new law leaves millions of tons of sediment piling up at Ohio's ports.

Hydrologic History

The research is rooted in northwestern Ohio, a region that formerly boasted a 4,000-square-kilometer marsh dubbed the Great Black Swamp. The swamp "was the kidneys of the area, filtering the nutrients and making sure the water Lake Erie is receiving was clean," said Vázquez-Ortega.

Colonizers weary of the knee-deep mud and clouds of mosquitoes gradually drained the area in the mid-1800s, easing navigation but increasing the export of sediments from the land. The watershed is now more than 72% agricultural.

Nutrients like nitrogen and phosphorus naturally enter lakes through sediment export, but farm practices—like draining

Soybeans grow in buckets in a greenhouse at Bowling Green State University. Credit: Angélica Vázquez-Ortega and fertilizing fields—accelerate the process. Once nutrients enter Lake Erie, they tend to stay there, eventually accumulating in sediments on the lake floor.

Those sediments require annual dredging to keep ports viable. Ohio dredges 1.5 million tons of sediment from its eight ports each year, and the Port of Toledo accounts for more than half that figure. Until recently, Toledo would dump dredged sediment into open water, a common practice that introduces phosphorus and nitrogen back into the water column and buries benthic communities on the seafloor. Ohio banned open-water dumping of dredged sediment, effective in 2020, forcing ports to find a process for storing their sediment. For now, Toledo is building artificial islands on the lakefront.

"This is a completely new challenge for Ohio," said Vázquez-Ortega.

Green algae mats coat Lake Erie near its western shore. Credit: NASA Earth Observatory image by Joshua Stevens, using MODIS data from LANCE/EOSDIS Rapid Response

More Sediment, More Soybeans

Agriculture could be a possible destination for dredged sediment, according to results from Vázquez-Ortega's lab published in *Journal of Environmental Quality* (bit.ly/dredged-sediments). In a greenhouse experiment, sediment from the Port of Toledo increased crop growth with no significant loss of nutrients in percolated water.

The study created four soil combinations, blending material from a local farm with dredged material from the Port of Toledo at sediment ratios of 0%, 10%, 20%, and 100%.

Soybeans grown in soil with more Lake Erie sediment grew heftier root systems and generated higher soybean yields in a study at Bowling Green State University. Credit: Angélica Vázquez-Ortega

Dredged sediment introduced more organic content, giving the test soils a lower bulk density and allowing roots and water to penetrate into the less compact soil. Samples with more Lake Erie sediment grew heftier root systems and generated higher soybean yields. The study demonstrated that Lake Erie sediments can improve crop yield without the use of additional fertilizers.

"All that information is really necessary for convincing a farmer this is an option."

Farming Out the Research

Despite promising results, there's plenty left to research. What crops grow best and at what sediment percentages? What if industrial contaminants are in the soil? Will this work outside the greenhouse on an actual farm?

"All that information is really necessary for convincing a farmer this is an option," said Vázquez-Ortega.

Economics and logistics are other key concerns. With 1.5 million tons of material, Ohio can give nutrient-rich sediment away for free. But would anyone want it?

In the study, the greatest soybean yield came from the 100% dredged sediment sample. That's not a feasible ratio for farms, though. Sediment is heavy, and transporting it is expensive. Even at 10% application, a farmer would need 100 tons of dried sediment per acre, estimated Keith Reid, a soil scientist with Canada's Department of Agriculture and Agri-Food. In addition, he said, spreading tons of sediment would require heavy machinery, which would compact the soils and remove any benefits of lower bulk density.

"It's a good start at looking at the potential for uses of soil amendment," Reid said of the study. "It's fair to safely say there was no negative impact. It's hard to say if there was a real large positive impact."

Any new method for farming must demonstrate effectiveness and affordability, and Vázquez-Ortega recognizes the work left to do. "It's a very preliminary step," she said of the study. She's now collaborating with the Ohio Environmental Protection Agency and the Ohio Lake Erie Commission, among other parties, on a 2-year farm test.

The study is a step toward finding a beneficial use for sediment that preserves the ports and protects the lake. But until the process makes economic and agronomic sense, sediments will remain all dredged up with nowhere to grow.

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

Forecast: 8 Million Energy Jobs Created by Meeting Paris Agreement

Opponents of climate policy say curbing fossil fuel emissions will kill jobs, but a new study shows that switching to renewables would actually create more jobs than a fossil fuel–heavy future would. The tricky part is ensuring that laid-off workers have access to alternative employment.

Globally, jobs in the energy sector are projected to increase from 18 million today to 26 million in 2050 if the world cuts carbon to meet the well-below 2°C target set by the Paris Agreement, according to a model created by researchers in Canada and Europe. Renewables will make up 84% of energy jobs in 2050, primarily in wind and solar manufacturing. The new study was published earlier this summer in *One Earth* (bit.ly/jobs-energy-sector).

In contrast, if we don't limit global warming to below 2°C, 5 million fewer energy jobs will be created.

The Future Is Looking Bright for Solar and Wind

The Intergovernmental Panel on Climate Change's latest physical science assessment predicted that climate will be 1.5°C warmer than preindustrial levels by the 2030s unless there are strong, rapid cuts to greenhouse gases in the coming decades. Such cuts will necessitate a greater reliance on sustainable energy sources.

In 2020, renewables and nuclear energy supplied less than a quarter of global energy, according to BP's 2021 report (bit.ly/bp-21-report).

This number is expected to rise, however, in part because solar photovoltaics and wind are now cheaper than fossil fuels per megawatt-hour and because many countries have set aggressive emissions-cutting goals.

According to the new study, many regions will gain energy jobs in the transition, including countries throughout Asia (except China), North Africa, and the Middle East, as well as Brazil and the United States. Although fossil fuel extraction jobs will largely disappear, "massive deployment of renewables leads to an overall rise in jobs," wrote the authors.

But not all countries will be so lucky: Fossil fuel–rich Australia, Canada, China, Mexico, South Africa, and sub-Saharan African countries will likely lose jobs overall.

Only jobs directly associated with energy industries, such as construction or maintenance, were included in the study. Other reports have included adjacent or induced jobs such as those in fuel transport, government oversight, and the service industry.

The tricky part is ensuring that laid-off fossil fuel workers have access to alternative employment.

Previous studies estimated a larger increase in energy jobs, using numbers compiled from the Organisation for Economic Co-operation and Development.

The new study instead compiled data from primary sources by mining fossil fuel company reports, trade union documents, government reports, national databases, and other sources that cover 50 countries representing all major players in fossil fuels and renewables. Lead study author Sandeep Pai ran the numbers through an integrated assessment model housed at the European Institute on Economics and the Environment. The model calculates job growth projections under different climate policies and social and economic factors. Pai is a lead researcher at the Just Transition Initiative supported by the nonprofit policy research organization the Center for Strategic and International Studies and the Climate Investment Funds.

The price of onshore wind energy per megawatt-hour plummeted by 70% between 2009 and 2019, making it cheaper to consume than fossil fuels. Credit: Science in HD/Unsplash

Calls for Just Transitions

Crucially, the study found that nearly 8 million (31%) of the 26 million jobs in 2050 are "up for grabs," said study author Johannes Emmerling, a scientist at the European Institute on Economics and the Environment.

These jobs in renewable manufacturing aren't tied to a particular location, unlike in coal mining.

Pai concurred. "Any country with the right policies and incentives has the opportunity to attract between 3 [million and] 8 million manufacturing jobs in the future."

Recently, countries have begun putting billions of dollars toward "just transition," a loose framework describing initiatives that among other things, seek to minimize harm to workers in the fossil fuel industry. Concerns include salary loss, local revenue, and labor exploitation.

What can be done? Just transition projects may include employing fossil fuel workers to rehabilitate old coal mines or orphan oil wells, funding community colleges to train workers with new skills, supporting social services like substance abuse centers, and incentivizing local manufacturing.

"The just transition aspect is quite critical," Pai said. "If [countries] don't do that, this energy transition will be delayed."

LUT University energy scientist Manish Thulasi Ram, who was not involved in the study, thought the latest research underestimated the job potential of the energy transition. Using a different approach, Ram forecast that close to 10 million jobs could be created from battery storage alone by 2050—a sector not considered in the latest analysis.

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

Planning and Planting Future Forests with Climate Change in Mind

Lumber prices were up by more than 500% in some areas this year, and people were even poaching trees from public forests for home projects, but this pandemic surge in lumber demand was a short-term threat to trees compared with the ongoing climate emergency. In some regions, temperatures are warming too fast for trees to catch up.

Because trees take decades to grow, today's well-adapted seedlings may be unprepared for the future climate. That can have consequences far beyond the forest. Trees that are not adapted to their climate are more likely to succumb to pests and disease, and dead trees intensify forest fires. Fires lead to increased flood risks, and floods drag dust and dirt to downstream water systems, which can clog pipes and strain treatment systems.

"It's just a vicious vortex that arises when trees are maladapted because of climate," said Greg O'Neill, a climate change adaptation scientist for the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development.

O'Neill and forestry researcher Erika Gómez-Pineda are coauthors of a recent article published in the *Canadian Journal of Forest Research* that makes the case for forestry practices to incorporate a process known as assisted population migration, in which seeds are moved to colder climates within the species' natural range (bit.ly/assisted-migration). This can help foresters capitalize on existing adaptations and bolster their forests for future climate change.

"It's just a vicious vortex that arises when trees are maladapted because of climate."

Searching for Seeds

The study addressed two seed stock questions: Where will British Columbia have problems, and where are solutions already growing in the United States? Using Representative Concentration Pathway 4.5 projections, the authors identified key parameters, including average precipitation, average temperature, and growing degree days for British Columbia's ecosystems in the year 2055. The study design assumes an impending planting date in 2040 and accounts for the first years of growth when trees are most susceptible to stress. Out of 207 seed zones, 44 (about 21%) were at high or moderate risk of losing adapted domestic seed supply by 2040, suggesting that these zones may soon lack domestic seeds worth planting.

Next, the researchers mapped areas of the Pacific Northwest and British Columbia where historical growing conditions in 1945 (the earliest era of province-wide weather records) mirrored the expected climate in 2055. O'Neill and Gómez-Pineda found that a matching climate area greater than 20,000 square kilometers existed in the United States for 42 of British Columbia's 44 at-risk seed zones—that's an area about twice the size of Puerto Rico. Even considering lakes, slopes, and neighborhoods that would reduce the feasible seed access area, that's still a large region where Canadian foresters could secure heartier seeds.

However, when assessing the possibility of putting assisted migration practices into place, it is important to keep phenology in mind, said Csaba Mátyás, a professor emeritus of forestry at the University of Sopron in Hungary who was not involved in the study.

Trees, Mátyás said, develop a "physiological clock" that assesses climate patterns to guide growth. Generations of trees can gradually adjust that timing, but "these horrible changes we are expecting will happen in 50–100 years, which is one generation," Mátyás said. "You cannot rely on natural processes because [they're] too slow."

Mátyás noted that planning is important and that seeds adapted for the future may struggle at the time of planting. Local seeds that enter artificial plantations will naturally outcompete transferred seeds. "You should be quite careful in the first 10–20 years," he cautioned. Planting for the future works only if seedlings survive the present.

British Columbia forestry staff pick spruce cones in a seed orchard managed by the province. Credit: Kat Spencer

Adaptive Capacity and Culture Change

Assisted population migration is already in practice in some places. British Columbia, which plants around 300 million trees each year and exports a significant share of U.S. lumber sales, switched from local seed selection to climate-based selection in 2018.

"Climate change and these environmental problems don't respect borders. If we don't pay attention to climate in selecting seed sources for reforestation, then we have serious problems ahead of us."

A clear-cut line separates Canada from the United States. Cross-border collaboration may be needed to ensure forest health in Canada under climate change. Credit: Carolyn Cuskey, CC BY 2.0 (bit.ly/ccby2-0)

Ontario followed in 2020. What's more, the U.S. Forest Service launched the Seedlot Selection Tool in 2009 to guide planting decisions.

However, borders complicate the seed-sharing process, and barriers persist. States like California have botanical border patrols, which keep out unwanted pests but complicate seed sharing. In most areas, local seeds are more convenient to access.

"It's a complicated set of fragmented laws that determines when a species can be transported or planted," said Alejandro Camacho, an environmental law professor at the University of California, Irvine.

But forests are traditionally managed to increase yield, which lessens resistance to population migration. "National forests generally have more built-in legal adaptive capacity than other public lands," Camacho said. But those rules, he noted, don't ensure the promotion of ecological health.

O'Neill believes that forestry needs a culture shift to face climate change. "We're not in the habit of doing this," he said of migrating seeds from other jurisdictions. "Climate change and these environmental problems don't respect borders. If we don't pay attention to climate in selecting seed sources for reforestation, then we have serious problems ahead of us."

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

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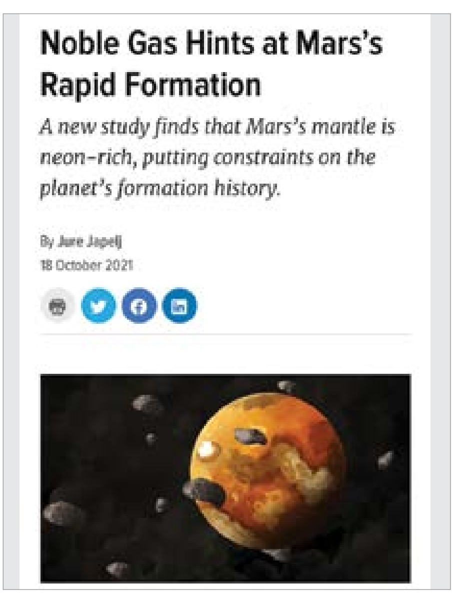

Noble Gas Hints at Mars's Rapid Formation

A new study finds that Mars's mantle is neon-rich, putting constraints on the planet's formation history.

By Jure Japelj
18 October 2021

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Megaripples on Mars: How to Name Wind-Shaped Features on the Red Planet

Straight-crested transverse aeolian ridges in the lower part of the left image give way to more complex star-shaped sand dunes in this terrain southwest of Schiaparelli Crater on Mars. Credit: NASA/JPL-Caltech/University of Arizona. Two types of aeolian landforms are visible in the right image: large transverse aeolian ridges and the smaller ripples that run perpendicular to them. Credit: NASA/JPL-Caltech/University of Arizona

Spacecraft on Mars have captured images of barren, desertlike landscapes complete with dunes of sand. But the windswept features are not identical to their terrestrial counterparts. The surface of the Red Planet is dotted by mid-sized sand masses not found on Earth. These features go by a variety of names: megaripples, sand ripples, sand ridges, and the less melodic transverse aeolian ridges (TARs) chief among them. But the nomenclature is inconsistent, causing confusion that hampers scientific advancement. Now new research has proposed an official naming scheme for Mars's wind-formed features.

"Because we're seeing new things on Mars, people have adapted what they are calling things," said Mackenzie Day, a researcher at the University of California, Los Angeles. Day and James Zimbelman of the Smithsonian Institution coauthored the new paper, published in the journal *Icarus* (bit.ly/mars-megaripples). "People have adapted in slightly different ways."

Broadly based, the new system classifies aeolian, or wind-created, features by size and geomorphology.

"As we're getting new information, having a standard nomenclature makes sure everybody is on the same page," Day said. "If we're all talking about the same thing in the same way, it makes it easier as a scientific community to move forward in understanding what's going on."

Blowing in the Wind

Aeolian bedforms are piles of moving sand brushed across the planet's surface by the wind. On Earth, the largest of these features are sand dunes, which can stretch for tens to hundreds of meters in length. Small ripples only a few tens of centimeters long can be carved on top of these dunes.

"Bedforms are really amazing interactions between the atmosphere and the surface," said Serina Diniega, a research scientist at NASA's Jet Propulsion Laboratory who was not associated with the new paper. "If you see one, you immediately have a whole bunch of information about the environment."

In addition to dunes and ripples, Mars has a third type of bedform: transverse aeolian ridges. TARs appear to have been created by the wind but move on much slower timescales than their fellow bedforms and seem to be coated with a layer of fine-grained dust.

Day and Zimbelman proposed a broad frame of terminology for ripples, TARs, and dunes that relies first on the size and geomorphology of the features. As surface observations (anticipated soon from Curiosity and Perseverance) allow scientists to classify grain size and dust cover, the terminology can be further constrained.

Small ripples, for instance, are measured on centimeter scales in height and are classified as straight crested. Megaripples are measured at less than a meter in height and may be straight crested or sinuous. Unlike small ripples, megaripples may include coarse grains. TARs are classified as larger than a meter in height and straight crested. Dunes, the largest aeolian bedforms on Mars, are classified as taller than 3 meters and have wildly varying geomorphologies: from straight crested or sinuous to radially symmetrical stars.

"Using a classification based on looking at both Earth and Mars is better than a classification system based only on Earth."

According to Ryan Ewing, a geologist at Texas A&M University who was not involved in the new study, the biggest challenge of a settled nomenclature will be agreeing on the processes that created TARs. "I think as we uncover more about how sediments move on Mars by wind, that will help the community refine their definitions of these [features]," he said.

"I really like this paper because it's attempting to apply some sort of structure around these terms," said Diniega. "Using a classification based on looking at both Earth and Mars is better than a classification system based only on Earth."

Sand Through the Solar System

Bedforms aren't limited to Earth and Mars. They've been spotted on Venus and on Saturn's moon Titan, and there have been signs of them on Pluto and Comet 67/P.

"Every place that has an atmosphere—and even places that don't have an atmosphere—we see an example of these bedforms," Diniega said.

The new classification system should work on these bodies as well.

"As we start exploring the solar system more, like sending Dragonfly to Titan, it would be nice to have a nomenclature that could be applied independent of what planet you're on," Day said.

By **Nola Taylor Tillman** (@NolaTRedd), Science Writer

The Understudied Risks of Low-Magnitude Eruptions

A minor eruption on Fimmvörðuháls (close to Eyjafjallajökull in Iceland) could have major repercussions for international communications and economics. Credit: Boaworm/Wikimedia, CC BY 3.0 (bit.ly/ccby3-0)

Lara Mani grew tired of hearing about the Yellowstone supervolcano. Every so often, another news story would appear, proclaiming that the Yellowstone caldera system could erupt with such ferocity that the impacts could cascade into a global catastrophe. "Yes, there's plausibility in that," said Mani, a research associate at the University of Cambridge's Centre for the Study of Existential Risk, "but that's not the only mechanism. There's another way that can happen."

Smaller eruptions, depending on where they occur, could also have catastrophic impacts, Mani thought. Historically, researchers have focused largely on the physical risk—the magnitude of potential eruptions. That's at least in part because the vulnerability side—the transport routes, communication networks, and other infrastructure that if disrupted would affect societies around the globe—has become a problem only more recently.

"Most of the vulnerability is a relatively new (late 20th–21st century) product of how we humans have changed our technologies, economies, and flow of services," said Chris Newhall of the Earth Observatory of Singapore. But we've already seen how small eruptions can lead to major disruptions. Consider the 2010 eruption of Eyjafjallajökull volcano in Iceland, which grounded more than 100,000 flights and cost the global economy upward of $5 billion.

"That should never have reached the global platform that it did; it was such a small eruption," Mani said. "Why? What's the mechanism behind that? What does this mean? That's where it started." In a new study in *Nature Communications,* Mani and her colleagues brainstormed identifying areas where smaller eruptions could combine with human-made vulnerabilities with catastrophic results (bit.ly/lower-magnitude). The new knowledge could lead to risk assessments and changes to preparedness.

Pinch Points

Mani and her colleagues began by looking at choke points along shipping routes—a focus that was highlighted this year when a container ship ran aground in the Suez Canal, bringing a major global trade route to a halt. They also looked at air traffic routes and other critical infrastructure like underwater cables and manufacturing hubs. The team identified seven "pinch points," where active volcanoes overlapped with these vulnerabilities. Four of the points were clustered together in a highly populated geographic corridor extending from Southeast Asia through the South China Sea. "It makes sense that where you have people, you have systems to sustain those societies," Mani said.

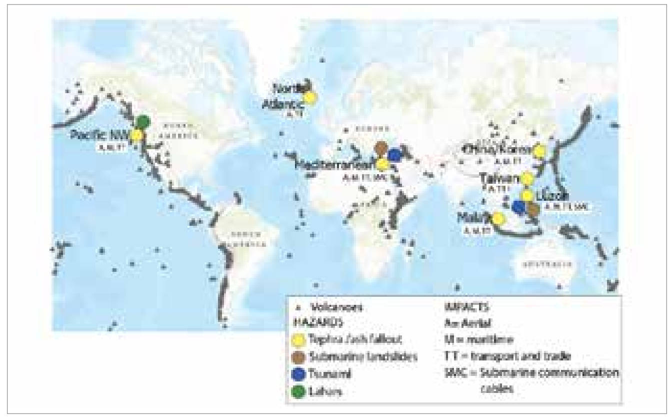
"We've prioritized efficiency over resilience. If something goes wrong, there isn't an alternative."

A small eruption at Mount Paektu on the China–North Korea border, for example, could disrupt air routes between Seoul and Osaka or Tokyo—some of the busiest routes in the world. In the Luzon Strait, a landslide or tsunami caused by an eruption along the Luzon Volcanic Arc could sever critical submarine cables connecting countries from China and Taiwan to the Philippines. Some 40% of global trade passes through the Strait of Malacca (between Malaysia and Indonesia); an eruption of any number of volcanoes along the Indonesian archipelago could shut down air and maritime traffic. The cascading impacts of these events are unpredictable and difficult to calculate: The 6-day blockage of the Suez Canal, for example, cost the Egyptian government as much as $90 million in lost toll revenue. Global trade revenue sank by as much as $10 billion.

"We've prioritized efficiency over resilience," Mani said. "If something goes wrong, there isn't an alternative."

Taiwan is home to the Taiwan Semiconductor Manufacturing Company (TSMC), responsible for manufacturing 90% of the world's advanced microchips and nodes. An eruption in the Tatun Volcano Group could close the port of Taipei, isolating TSMC from the rest of the world. "Anything that happens to TSMC…sends a shock wave [through society]," said Mani. "Everybody knows that it's a critical vulnerability, but no one has ever thought about what it's vulnerable to."

The team also identified pinch points in the Mediterranean, the North Atlantic, and the Pacific Northwest, where the eruption of one of the Cascades volcanoes could melt glaciers or ice caps, triggering a debris flow that could potentially reach all the way to Seattle.



Pinch points mark the clustering of critical systems and infrastructures with regions of lower-magnitude volcanic activity. These pinch points are presented with the likely associated volcanic hazard and the potentially affected systems. Credit: Mani et al., 2021, https://doi.org/10.1038/s41467-021-25021-8

Mani hopes that pointing out these vulnerabilities in global systems will ultimately help to build resilience. "My hope is that it will raise some questions to the volcanology community, the volcanic risk community, to start having these discussions about what this risk really looks like," she said, "so that disaster managers, international organizations, and governments can start thinking about mitigation and prevention."

By **Kate Wheeling** (@KateWheeling), Science Writer

When Wild Weather Blew Old Sea Ice South

Robbie Mallett experienced the perennial sea ice in the Arctic during a 2019 research expedition. Credit: Robbie Mallett

Robbie Mallett often thinks about the first time he stood on old sea ice in the Arctic.

"It's like a landscape," he said. "It's got ridges and landforms almost. It's just an amazing place. And I think it's a really sad thing that we're basically losing a whole place."

Mallett is a Ph.D. student and sea ice researcher at University College London. His most recent research accentuates how the loss of this sea ice landscape could accelerate because of one unique characteristic: It can float away.

In a paper published recently in *Communications Earth and Environment,* Mallett and other researchers described how powerful winds during the winter of 2020–2021 blew a vast amount of sea ice south into warmer waters, putting it at risk of melting over the summer (bit.ly/wind-arctic).

A Sprawling High-Pressure System

The investigation started after Mallett received an interesting email from his graduate adviser, Julienne Stroeve. She told him that an area of high pressure over the Beaufort Sea near the north coast of Alaska (the Beaufort Sea high) was unusually strong.

"It almost wasn't appropriate to call it the Beaufort Sea high at all," Mallett said. "It was just this huge, sprawling, high-pressure system that dominated the whole Arctic Ocean."

The location and strength of the Beaufort Sea high, associated with a sudden warming in the stratosphere on 5 January 2020, generated record-breaking surface winds that persistently swirled around the center of the Arctic Ocean. Mallett wanted to investigate how much older sea ice was at the whim of these winds.

Old Sea Ice Blew into the Beaufort Sea

Scientists are particularly interested in older sea ice, called perennial sea ice, that has lasted through at least one melt season. Perennial ice is thicker, so it has a better chance of surviving the summer months when its cooling properties are most crucial. "It shows up when you need it," Mallett said.

The researchers used a series of satellite images in the microwave spectrum to track the ice flow over months. They also used data from the European Space Agency's CryoSat radar altimeter, which bounces pulses off the ice's surface to determine its age based on how thick it is. "When you combine that with how the ice is moving, you can see what the old ice is getting up to," said Mallett.

The winds associated with the strong Beaufort Sea high blew ice westward from north of Greenland toward Alaska. The winds flushed first-year ice out of the Beaufort Sea, replacing it with old ice from the Arctic. By the end of the winter, nearly a quarter of all the perennial sea ice in the Arctic Ocean was in the Beaufort Sea, which is not a hospitable place for sea ice to spend the summer.

Warmer air and water temperatures in the southern Arctic Ocean put sea ice at greater risk of melting over the summer. Credit: NASA/Kathryn Hansen

"It's in a dangerous place," Mallett said. "It's in a place that is just much warmer, both in the air and water temperature."

"Thinner Ice Is More Mobile"

Thinner ice in the Arctic is associated with the warming climate, and although the researchers did not attribute the events of winter 2020–2021 to climate change, Kent Moore, a University of Toronto atmospheric physicist, expects that thinner ice was generally a factor in ice transport. "Thinner ice is more mobile," said Moore, who was not involved in the new research.

Moore was curious whether the ice tracked in 2020 was as mobile in other years when the Beaufort Sea high was extreme or the outcome was the consequence of thinner ice. If thinner ice were to blame, we might expect more ice to be blown around in the future.

"It almost wasn't appropriate to call it the Beaufort Sea high at all. It was just this huge, sprawling, high-pressure system that dominated the whole Arctic Ocean."

Thinning ice appears to be affecting a stretch of the Arctic Ocean known as the last ice area, which scientists predicted will retain ice even after other regions become ice free in the summer. This past summer, ice blew out of the last ice area, and Mallett and colleagues also found that ice left the region last winter, although Mallett said it's hard to know exactly how much.

"The last ice area may not be as resilient to climate change as we think," Moore said.

For now, though, it's not all bad news in the Beaufort Sea. New satellite data came out in early August, and Mallett said a lot of the ice was still intact.

"It's surprised me how tough that ice has been in the Beaufort Sea," Mallett said. "All we can do is wait for the next data release."

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

The Best Accidental Climate Treaty

The international treaty that phased out the production of ozone-depleting chemicals has prevented between 0.65°C and 1°C of global warming, according to research.

The study also showed that carbon stored in vegetation through photosynthesis would have dropped by 30% without the treaty, which came into force in 1989.

Researchers from New Zealand, the United Kingdom, and the United States wrote in *Nature* that the Montreal Protocol was essential in protecting carbon stored in plants (bit.ly/carbon-sink). Studies in the polar regions have shown that high-energy ultraviolet rays (UVB) reduce plant biomass and damage DNA. Forests and soil currently absorb 30% of human carbon dioxide emissions.

"At the end of our simulations, which we finished around 2100, the amount of carbon which is being taken up by plants is 15% the value of our control world where the Montreal Protocol is enacted," said lead author and atmospheric scientist Paul Young of Lancaster University.

In the simulation, the UVB radiation is so intense that plants in the midlatitudes stop taking up a net increase in carbon.

Plants in the tropics fare better, but humid forests have 60% less ozone overhead than before, a state much worse than was ever observed in the Antarctic ozone hole.

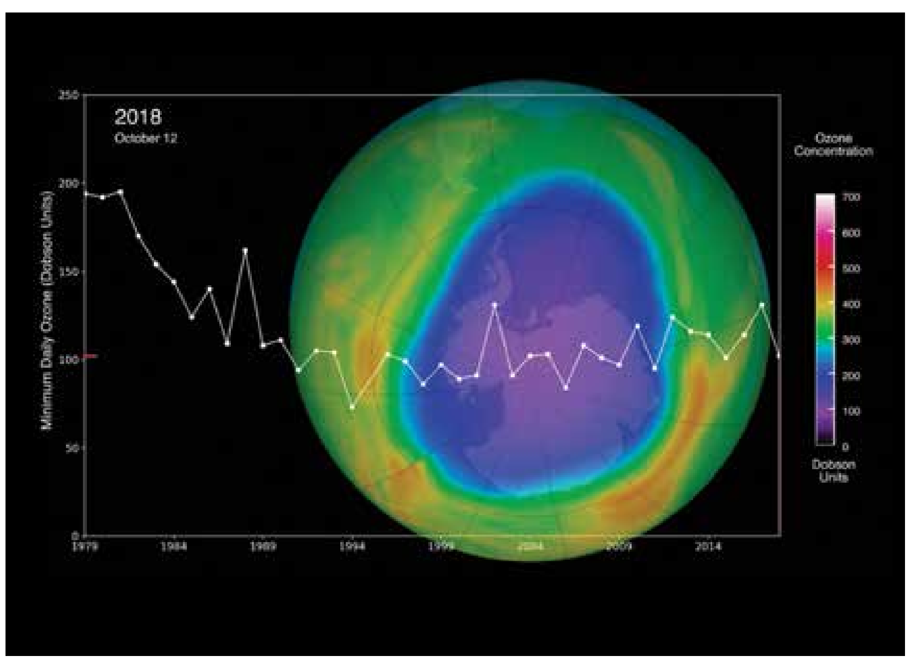
A "World Avoided"

The study used a chemistry climate model, a weather-generating tool, a land surface model, and a carbon cycling model. It linked ozone loss with declines in the carbon sink in plants for the first time

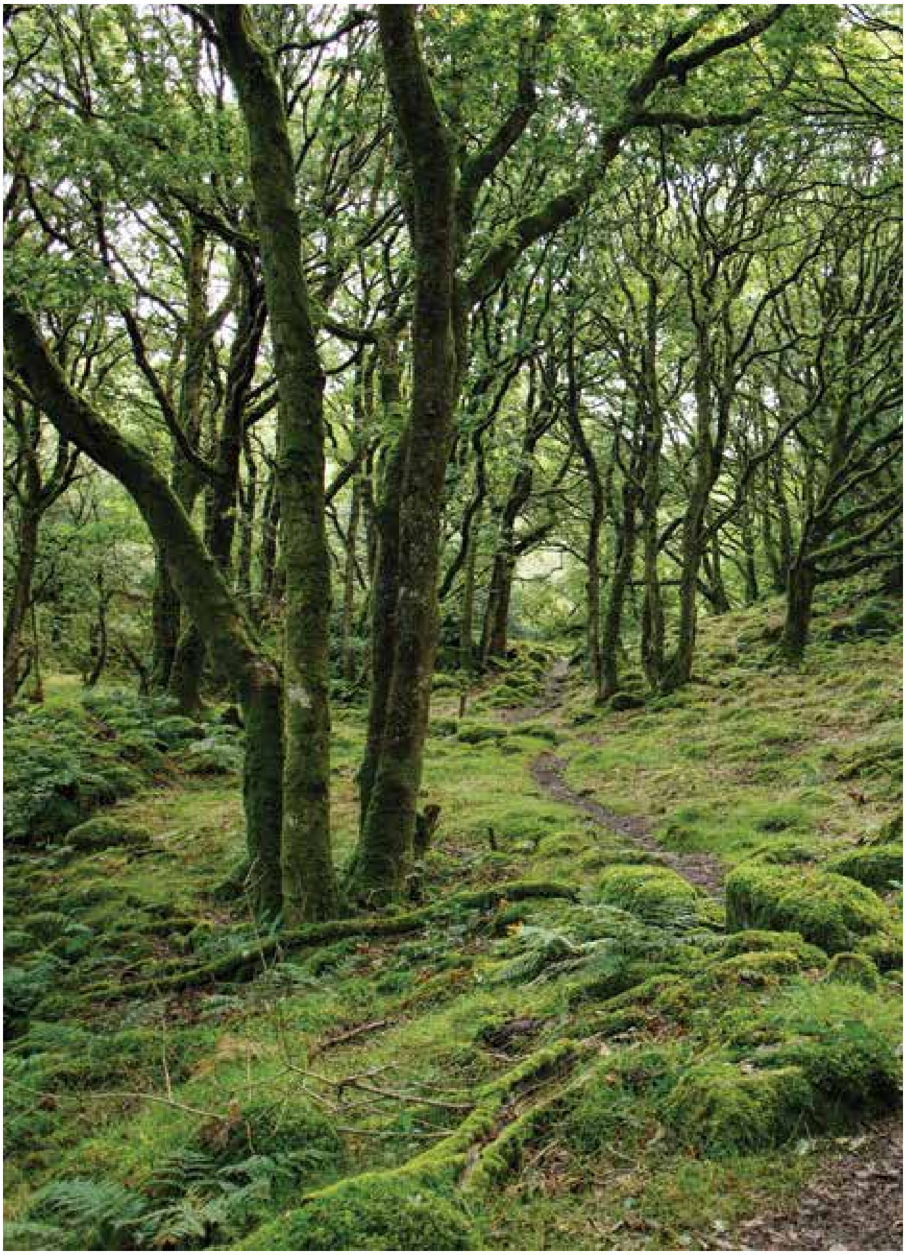
Chlorofluorocarbons (CFCs), ozone-depleting chemicals phased out by the Montreal Protocol, are potent greenhouse gases. The study estimated that CFCs would warm the planet by an additional 1.7°C by 2100. Taken together, the damage from UVB radiation and the greenhouse effect of CFCs would add an additional 2.5°C warming by the century's end. Today the world has warmed, on average, 1.1°C at the surface, leading to more frequent droughts, heat waves, and extreme precipitation.

Carbon dioxide levels in the atmosphere would reach 827 parts per million by the end of the century too, double the amount of carbon dioxide today (~412 parts per million).

The work analyzed three different scenarios: The first assumed that ozone-depleting



The ozone layer over Antarctica has stabilized and is expected to recover this century. Credit: Amy Moran/ NASA Goddard Space Flight Center



The planet would store 580 billon tons less carbon in plants and soil by the end of the century if the Montreal Protocol had never existed. That's more than all the carbon held in Earth's forests. Credit: Marc Pell/Unsplash

substances stayed below levels in 1960, when massive production kicked in. The second assumed that ozone-depleting chemicals peaked in the late 1980s before tapering off. The last assumed that ozone-depleting chemicals increased in the atmosphere every year by 3% through 2100.

The last scenario, called the "World Avoided," assumed not only that the Montreal Protocol never happened but also that humans had no idea CFCs were harming ozone, even when the effects would become clear in the 2040s. The models also assumed one kind of UVB damage to all vegetation, when in reality, plants react differently.

"Change Is Possible"

"The Montreal Protocol is regarded as one of the most successful global environmental treaties," said University of Leeds atmospheric scientist Martyn Chipperfield, who was not involved in the research. "CFCs and other ozone-depleting substances are potent greenhouse gases, and the Montreal Protocol is known for having real benefits in addressing climate change by removing previous levels of high CFCs from the atmosphere."

The last scenario, called the "World Avoided," assumed that the Montreal Protocol never happened.

The Kigali Amendment to the Montreal Protocol in 2016 brought climate change to the forefront. Countries agreed to gradually phase out hydrofluorocarbons (HFCs), which are used in such applications as air conditioning and fire extinguishing systems. HFCs originally replaced hydrochlorofluorocarbons (HCFCs) and CFCs because they do not harm ozone. Yet HFCs are potent greenhouse gases.

The Montreal Protocol was the "best accidental climate treaty," said Young. "It is an example of where science discovered there was a problem, and the world acted on that problem."

Injecting sulfate aerosols into the stratosphere has been proposed as one geoengineering solution to slow global warming. "People are seriously talking about this because it's one of the most plausible geoengineering mechanisms, yet that does destroy ozone," Young said. Calculating the harm to the carbon cycle is "the obvious follow-up experiment for us."

The research highlights the importance of the U.N. Climate Change Conference of the Parties (COP26) in determining the success of worldwide climate targets.

Immediate and rapid reductions in greenhouse gases are necessary to stop the most damaging consequences of climate change, according to the Intergovernmental Panel on Climate Change.

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

Chile's Glacier Protection Law Needs Grounding in Sound Science

Glaciers have long been thought of as static, picturesque totems or as changeless coverings over permanently frozen landscapes, particularly among societies distant from mountains and the poles. However, as traditional mountain cultures with firsthand experience have long known and treasured—and as glaciologists, hydrologists, and climate scientists have deciphered and communicated—glaciers are by no means static. Rather, they are dynamic landscape agents and unmistakable indicators of rapid environmental transformation [*Gagné et al.*, 2014]. With widespread media coverage of anthropogenic climate change and the realization that glaciers are endangered species [*Carey*, 2007], popular perceptions are gradually changing, and scientists, grassroots movements, and policymakers are increasingly committing to developing legal protections for glaciers.

In 2006, legislative efforts to enact a glacier protection law in Chile started as a result of increasing concerns about how mining activities were endangering small glaciers in the north of the country [*Herrera Perez and Segovia*, 2019]. Around the same time, other initiatives affecting glacierized basins, such as the HidroAysén hydroelectric project, helped to galvanize local and national activists, who demanded stronger environmental action from the government. With the country facing significant challenges associated with a long drought affecting its most populated regions, environmentally focused legislation has become a main priority for many Chileans after the populace overwhelmingly requested a new constitution. The latest initiative related to glaciers, called the Ley sobre protección de glaciares (law for glacier protection), is still in discussion in the Senate chamber. Despite the law's admirable aims, in its current form it includes some flaws that, if passed, will undermine its effectiveness.

Chile's Crucial Cryosphere

Stretching roughly 4,300 kilometers from the Atacama Desert in the north to its northern border while spanning only about 180 kilometers on average between the Andes and the Pacific Ocean, Chile contains most of the ice and snow cover in the Southern Hemisphere outside the polar region. It also hosts a significant yet little-studied periglacial landscape characterized by permafrost features, including soils and rock glaciers, among others. Glaciers, snow, and permafrost are found along the Chilean Andes and across several climatic regimes, from nearly tropical to subantarctic, epitomizing the wide range of environmental conditions where these water reservoirs can grow and wane.

Chile's cold environments are part of the essence of the country, and socioeconomic development here is ineradicably linked to cryosphere dynamics. Agriculture, mining, drinking water provision, hydroelectricity, tourism, and ecosystem services depend, in one way or another, upon the presence of snow and ice. In the south, for example, the majestic glacierized Patagonian landscape attracts visitors from all over the world. In the semiarid north and center of the country, large agricultural areas, including Chile's world-renowned wine-producing regions, are watered largely by mountain streams nourished by ice and snow melt. In a sense, anyone enjoying a Chilean Carménère is likely tasting drops of the Chilean cryosphere.

With Chile facing significant challenges associated with a long drought affecting its most populated regions, environmentally focused legislation has become a main priority for many Chileans.

A legal framework that considers the latest technical and theoretical understanding of Chile's cold environments is essential for effective regulation and for maintaining the cultural and socioeconomic value these environments provide. Members—including ourselves—of the Sociedad Chilena de la Criósfera, the only scientific society in Chile dedicated to studying the country's cryosphere, and other geoscientists have appealed to the National Congress of Chile and the public to provide support and advice to develop scientifically sound and accurate legislation. However, we are increasingly concerned about the effectiveness of the glacier protection law because current iterations under discussion in the congress include misleading concepts and criteria.

Some Limitations of the Proposed Law

At the most basic level, we are alarmed by how these proposals use "cryosphere" and "glaciers" synonymously. The proposed legislation covers glaciers and permafrost, so a more accurate framework would entail protection of the entire cryosphere. However, there are more profound concerns that may become hard to correct once the law is enacted. Among others, these concerns include unfeasible definitions of what a glacier is, poor understanding of the relationship between glacial and periglacial environments, and impacts of the proposed legislation on key infrastructure.

Fundamentally, a glacier is a body of ice massive enough to flow under its own weight, a characteristic that sets it apart from perennial snowfields or smaller patches of snow and ice. Combining understanding from Glen's flow law, a fundamental glaciological tenet that relates ice flow velocity with slope and thickness [*Cuffey and Paterson*, 2010], with well-established relationships between glacier surface area and volume [*Bahr et al.*, 1997] offers guidance on the minimum size of an ice patch that can be considered a glacier.

During congressional discussions, overly simplistic definitions of glaciers based on flow properties and debris cover have been contrasted with definitions considering more operative yet technically contestable criteria, such as a minimum surface area threshold to be used for mapping and protection purposes under the law. Some proposals by members of the congress have argued that this minimum limit should be as small as 0.1 hectare (1,000 square meters). This threshold is much stricter than what is normally applied in the scientific literature, which suggests instead that a surface area of 1 hectare (about the size of a soccer field) may be a more reasonable threshold to use in mapping glacial inventories [*Paul et al.*, 2009; *Leigh et al.*, 2019].

A 0.1-hectare threshold would make it possible to misinterpret ephemeral firn or snow patches as bodies of glacier ice. Under a wide range of realistic glacier surface slopes, the flow law predicts surface velocities well within the uncertainty range of modern measurement techniques like high-precision GPS for average ice thicknesses (about 4 meters) corresponding to the 0.1-hectare threshold. Also, energy and mass balance research shows that Chilean glaciers can melt at rates in excess of 15 meters per year [e.g., *Kinnard et al.*, 2018]. Thus, plausible rates of 4 meters per year result in total melt out of a 0.1-hectare surficial frozen water body within a year or so, further supporting the idea that such small bodies should not be cataloged as glaciers in inventories.

Within the law, permafrost and periglacial environments are key elements to be protected, and rightly so. There is plenty of science suggesting that many areas experiencing water stress are covered by sediments and soils that may contain either perennial or seasonal ice [*Ruiz Pereira et al.*, 2021]. These environments are demarcated on the basis of morphological features, such as the presence of frozen ground, as well as climatic thresholds, particularly with respect to the elevation of the zero-degree isotherm (above which the air temperature is always below 0°C). Although these criteria are in line with established understanding of the conditions that sustain permafrost and rock glaciers [*Dobinski*, 2011], the current proposal and ongoing debate are flawed nonetheless because they do not consider the hydrological role of permafrost and periglacial areas. In high-elevation regions, including large areas of the Chilean Andes, water storage and drainage are sensitive to permafrost, rock glacier, and glacial changes. Therefore, overlooking this role is inexplicable, especially considering that the first article in the law explicitly indicates that the main reason for preserving glaciers, permafrost, and periglacial areas is their critical value as strategic water reservoirs.

Waterfalls pour from an outlet glacier in Queulat National Park in Chilean Patagonia. Credit: Alfonso Fernández

How Geoscientists Can Contribute

We understand some of the considerations and debates surrounding the glacier protection law in Chile—for example, over the minimum surface area threshold—on the grounds that lawmakers are hoping to forestall future legal battles over its interpretation and application. Such battles have occurred in Argentina following implementation of a law similarly intended to preserve that country's cryosphere. There, conflicting civil and private judicial challenges associated with the use of a 1-hectare threshold in the official glacier inventory have been launched, with the mining sector contending that the threshold was too restrictive and others saying it did not protect enough area. These challenges led to the indictment of the chief scientist in charge of compiling the inventory for allegedly failing to uphold the country's glacier protection law when he adopted the 1-hectare threshold, ironically punishing one of the few people who fought to use the most reliable scientific evidence in cryosphere protections.

As scientists, we know that enacting a law will not end conflicts over how to govern

Glaciologists traverse a valley glacier in central Chile to deploy sensors. Credit: Alfonso Fernández

Chile's glaciers and cryospheric environments. We want to build bridges between citizens and the government to inform expectations of the law on all sides and to provide clear and accurate information for policymaking. As Isaac Asimov said, "The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom." We echo this and believe there is a unique opportunity to fine-tune Chile's policymaking by implementing dynamic and updatable features in the country's cryosphere protection law.

The scale and preeminence of Chile's glacial and periglacial landscapes argue for the nation's responsibility and opportunity to lead the world in cryosphere protection.

For example, the law should establish panels of academic experts, citizens, and public officers tasked with regularly updating operative definitions used in the legislation and with reviewing the latest technical developments (e.g., improvements in methods for glacier inventorying and monitoring). This approach could facilitate assessment of potential effects of activities, such as tourism or the development of water management infrastructure, within glacierized and periglacial areas.

This practice is not new: Expert panels often support policy—related to the ongoing COVID-19 pandemic and to fisheries management, for instance—by providing guidance about implications of the latest research and by proposing and evaluating metrics. In the case of glaciers, such an advisory group could, for instance, study criteria for mapping small glaciers [*Leigh et al.*, 2019]. Considering the substantial seasonal and interannual dynamics and variation of glaciers, this kind of approach can help harmonize preservation and management.

Today we see with great hope that Chile is finally awakening to the value and fragility of its grandiose glacierized Andean landscapes, rather than turning its back, as celebrated French glaciologist Louis Lliboutry lamented during his 20th-century journeys through the Andes [*Lliboutry*, 1956]. The scale and preeminence of Chile's glacial and periglacial landscapes argue for the nation's responsibility and opportunity to lead the world in cryosphere protection. Thus, governmental actions regarding protection should serve as frameworks for other nations facing impacts of climate change in mountainous areas.

In our view, the current version of the proposed law regrettably suffers from uncertainties and omissions that could sow further conflict instead of the solutions expected by Chile's public. We assert that it can be improved significantly if the country's well-trained scientific community is consulted. This community is eager to cooperate in developing accurate regulation that can serve as a milestone for the rest of the world. We hope that the congress heeds our offer before passing misguided legislation.

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▶ Read the article at bit.ly/Eos-Chile-glaciers

Remembering *FLIP*, an Engineering Marvel for Oceanic Research

From our perch, surrounded by the undulating sea, we watch a single wave approach. The wind does not roar so much as it pushes. I recall childhood memories of standing on a train platform with my mom as an express line confidently coasted through the station, ruffling our coats as it sped by and creating just such a push. Today the wind at sea hovers at about only a Beaufort 6—a strong breeze—but it makes me feel small, nonetheless.

The approaching wave is not especially big—I've swum with bigger waves, coming face to face with rolling masses of water that traveled hundreds, if not thousands, of kilometers to meet me. But it's not small, either, and in this moment, I am overcome by the same sensation of being immersed in the sea and watching an oncoming wave. This time, though, as I track the propagating undulation, I am perfectly dry, dressed not in a swimsuit, but in grimy jeans, worn boots, and a spectacularly tacky, deli mustard-yellow Hawaiian shirt festooned with grape bunches.

Now the wave is here, an azure mass of water rolling toward us. As it surges and contorts around the incongruous steel structure supporting us above the water, the wave becomes unstable and breaks, throwing its celebratory whitecap directly under our feet and wetting our soles. The visible sign of breaking comes with its compulsory auditory signature, a resounding *crash*, eliciting uncontrollable, inarticulate, and giddy *whoops* of delight from my colleagues and me.

Our lapse in professionalism draws a rebuke from the captain, standing on the navigation bridge 6 meters above our heads, and we snap back to reality: It's fall 2017, and we are in the middle of the Southern California Bight, participating in a major scientific field study aboard a historic, one-of-a-kind oceanographic platform.

We scurry up a series of steel ladders and return to our duties. Later, as I lie in my bunk—a few meters below the waterline—I forgive myself. If seeing a wave that traveled across the ocean to meet you is a miracle of nature, then watching that wave roll by without so much as adjusting your balance is a miracle of engineering. And for that, we can afford some giddiness.

The Floating Instrument Platform, or FLIP, *which ended its operational life in 2020, was a unique platform for projects requiring a stable vantage over the ocean. This photo was taken during the 2017 Coupled Air-Sea Processes and Electromagnetic ducting Research (CASPER) field study. Credit: Jeremiah Brower, Research Technician, UC San Diego/Scripps Institution of Oceanography*

Out at Sea but High and Dry

The Floating Instrument Platform (*FLIP*) is a unique asset in the U.S. ocean research vessel fleet. Technically, *FLIP* is not a ship or a vessel; it is a platform. Well, to be precise, *FLIP* is a very, very large spar buoy, a type of cylindrical float that sits upright at the ocean surface and is specifically designed to respond minimally to surface wave motions.

This 109-meter-long buoy comprises what looks like the front of a ship that's had its aft section replaced by a 90-meter-long, 4-meter-wide steel pipe resembling the working end of a baseball bat. In its resting state, *FLIP* floats lengthwise at the ocean surface. For expeditions, it is towed out to sea and, living up to its name, flips 90° to stand vertically at the surface.

Flipping is achieved by quite literally scuttling (a nautical term for purposefully sinking) the ballasted tubular end of the platform. This controlled, partial sinking—often with the full complement of personnel and equipment aboard—is executed precisely and expertly by the crew, who must be eternally commended for their perfect record in 390 attempts. Although the whole process takes 20–30 minutes, most of the motion occurs in about 90 seconds, taking the platform from an angle of less than 20° to fully vertical. During this time, crew and passengers execute a slow-motion, Fred Astaire-like dancing-on-the-ceiling routine, sans tuxedo.

After the flip is complete, the "boat" section perches above the water surface. This section contains most of the usable space and sleeping quarters, which meet the comfort standards that satisfied a 1960s era Navy sailor—the word spartan comes to mind. All the interior scientific laboratory space, a galley, and other workspaces are connected by a network of exterior steel ladders and grates. Together with three foldable booms, they give the platform the appearance of a giant mechanical cephalopod or perhaps the treehouse of Peter Pan's Lost Boys reimagined for the movie *Waterworld*.

Conceived, designed, and built between 1960 and 1962, *FLIP* was originally intended

FLIP lies in its horizontal position as it is towed to a research location off the coast of California. Credit: John F. Williams/U.S. Navy, CC BY 2.0 (bit.ly/ccby2-0)

to allow collection of precise acoustic measurements at sea. Frederick Fisher and Fred Spiess almost casually presented their ingeniously engineered platform in a journal publication that ran barely 11 pages. By 1969, *FLIP* had been modified with booms—the arms of the aforementioned cephalopod—to facilitate additional science, and it was being used for major field campaigns.

FLIP was so well engineered to remain motionless amid the waves that during a deployment in the northern Pacific in late 1969, the entire crew had to abandon the platform after 3 days of confinement inside without any power. Tom Golfinos, *FLIP*'s long-serving captain, and esteemed oceanographer Robert Pinkel, both of Scripps Institution of Oceanography, recounted to me that large Pacific swells overtopped the platform, reaching 15 meters above the still water line and knocking out power. As it had been designed to do, *FLIP* simply stood impassively as these massive waves broke around it, vindicating its designers but terrifying its occupants.

Among its travels through the remainder of the 20th century and the early 21st century, *FLIP* was towed from San Diego to Barbados, drifted near the Hawaiian Islands, and was lashed by stormy seas off the Oregon coast. All the while, it provided exactly what Fisher and Spiess envisioned: a stable platform from which to make precise measurements at sea.

A Critical and Charismatic Buoy

The beauty and genius of *FLIP* is that it isolates us from the ocean. The greatest challenge to measuring ocean properties has always been, well, being on the ocean. It is remote, dangerous, alternately cold and hot, wet, salty, and always *moving*. In an almost metaphysical way, this colossal steel tube allows humans to exist immersed within the ocean while protected from its tantrums.

The physical concept and engineering practice of deploying spar buoys for scientific expeditions were not novel in the early 1960s. But designing a spar buoy to *hold* scientific expeditions was a boundary-pushing step. The ambition and spirit that Fisher and Spiess captured in their design, which expanded over the platform's decades of use, helped propel science, exploration, and discovery across the ocean sciences for more than half a century.

The greatest challenge to measuring ocean properties has always been, well, being on the ocean.

In my field of air-sea interactions alone, *FLIP* contributed to many discoveries. For example, it helped reveal how swells generated by distant storms travel across vast ocean basins, and it enabled scientists to make very accurate measurements of atmosphere-ocean transfers of energy and material (gas), information that remains widely used in numerical weather and climate prediction systems. More recently, scientists aboard *FLIP* directly measured fine-scale currents and wind patterns within centimeters to millimeters of the sea surface using techniques previously confined to controlled laboratory experiments.

In addition to being a supremely useful platform for scientific study, it was a charismatic buoy—and quite frankly, there are not many charismatic buoys. Simply put, it was interesting to think about, talk about, or just look at, and it left an impression on almost everyone who saw it, let alone on the "Flippers" who have been aboard during a flip.

Once, shortly after my time aboard *FLIP*, I launched into a lengthy explanation of my research when the man I was chatting with asked about my work. Seeing the glazed look come over his eyes (which speaks more to the quality of my explanation), I changed tack and just showed him a picture of *FLIP* to illustrate what I "do." Immediately, his interest returned as he recognized *FLIP* and recounted how he had learned about it in his fifth-grade science class. Indeed, *FLIP* was a tangible icon with which many in the science-interested public identified.

A Month Aboard a Most Unusual Platform

In October 2017, with a freshly minted Ph.D. in applied marine physics, I spent about 35 days aboard *FLIP*, and it definitely made a lasting impression on me as well. I was aboard as part of the science team for the U.S. Navy-funded Coupled Air-Sea Processes and Electromagnetic ducting Research (CASPER) program, which involved an interdisciplinary and international cohort of scientists from several academic universities and federal research laboratories. The scientific goal of CASPER was to better understand how the atmosphere and the ocean interact, as well as how this atmosphere-ocean coupling affects electromagnetic energy traveling in the marine environment. The CASPER science team had conducted a field campaign offshore North Carolina in 2015 and then commissioned *FLIP* for its West Coast campaign during fall 2017.

In some ways, being aboard *FLIP* was like scientific cruises aboard more horizontal research vessels. Ship life revolved around your watch, the designated period when you do the three primary shipboard activities:

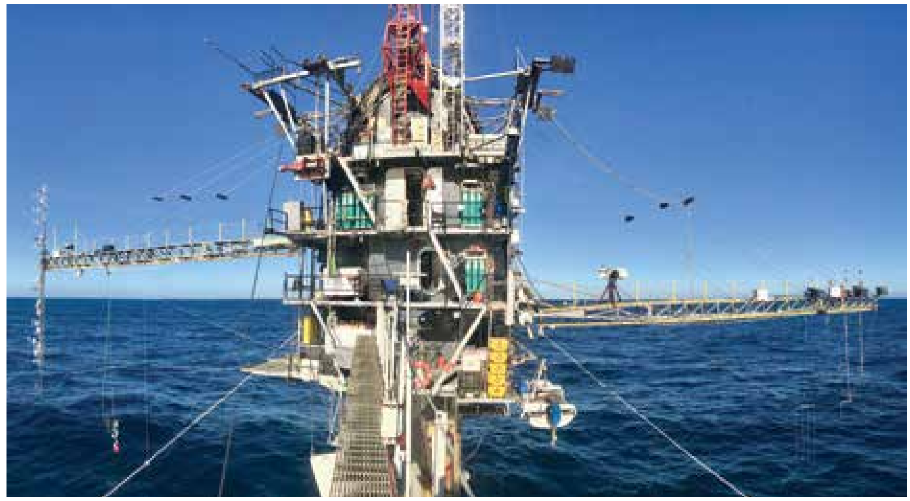
work, wait, and eat (sleep, the sanctified fourth activity, is done off watch). Also similar is how you are continually steeped in the aromas of fresh paint, burnt diesel fuel, and brine.

However, in many other ways, time aboard *FLIP* is not like on any other research cruise. *FLIP* bobs; it does not translate (i.e., move under its own propulsion). This difference in motion mitigates sea sickness yet leaves passengers with the uncomfortable sense that they've been marooned at sea. Also, all the livable space is vertically stacked, with hallways being replaced by ladders, which made simply going to bed a challenging, multistep process.

After donning class IV laser safety goggles—because of the fascinating nighttime experiments your colleagues are running outside—and noise-blocking earmuffs, you climb down three exterior ladders, make your way through the generator room (hence the earmuffs), and maneuver onto a ladder extending down into the darkness of the spar, or tube, section of *FLIP*. Through a bulkhead hatch at the bottom of this ladder is yet another ladder to scale down—but don't forget to first secure the hatch, quietly, without waking up sleeping scientists. Then, finally, you can climb into your own bunk and try to fall asleep to the sound of waves, hoping that you don't have to use the head (the bathroom) some 12 meters above you in the middle of the night.

Its peculiarities and inconveniences aside, *FLIP* was essential for achieving the objectives of CASPER because we needed a stable vantage from which to make measurements, which *FLIP* offered, especially compared with typical oceangoing ships. The data we collected from *FLIP* in 2017 have already given us new, fundamental insights into these physical processes.

For example, we are developing new tools to understand how electromagnetic signals propagate differently in various marine atmospheric conditions, techniques that are important for improved maritime communication and shipboard detection of low-flying objects for national security interests. We are also discovering how ocean internal waves leave distinct imprints on the atmosphere through complex and previously unknown mechanisms, and are getting a firmer grasp of the influence of ocean surface waves on atmospheric processes and atmosphere-ocean exchanges that regulate weather and climate. The CASPER team is also using our measurements to inform and validate sophisticated numerical models to help understand these processes and to generalize and translate our findings to other ocean conditions.



FLIP *is a very large spar buoy: It sits upright at the ocean surface and is specifically designed to respond minimally to surface wave motions. The author took this photo of* FLIP*'s "face" during the 2017 CASPER field study from the end of one of the platform's three foldable booms, aptly named Face Boom. Credit: David G. Ortiz-Suslow*

The Sun Sets on *FLIP*

My time aboard *FLIP* was short, but being part of the platform's legacy has been a truly humbling experience. Barring a major intervention, the fall 2017 cruise was *FLIP*'s last. In September 2020, the U.S. Navy ended its support of the platform, and its era of operational use came to an end. Although the pandemic was not the cause of this eventuality, it meant *FLIP*'s transition to emeritus status came without an opportunity for a public good-bye or any well-deserved fanfare.

Similar to the now defunct Arecibo Observatory in Puerto Rico, *FLIP* was a creation from a bygone era. Its drift into the sunset comes as research priorities and interests in the Earth sciences are shifting. *FLIP* was all steel and analog components, but the future will be built with lightweight alloys, carbon fiber, and autonomous systems. There is, of course, the understandable reality that exploring new horizons requires new technologies and that resources to support these explorations are finite.

In short, everything has an expiration date—not even a Hollywood credit helped Arecibo in the end. However, like its *Boricua* cousin of the planetary sciences, *FLIP's* legacy goes beyond the innumerable discoveries it enabled, embodying human ingenuity, curiosity about the natural world, and the drive to witness its unperturbed beauty.

FLIP's history and significance in oceanography are being actively discussed in the scientific community. My reflection here is only one perspective on a career that spanned decades and involved countless individuals. Given that my experience with *FLIP* came from its last chapter, I feel it is important to recognize the giant upon whose shoulders I and other researchers have stood. That giant comprised not so much the platform itself, but the engineers and shipwrights who designed, built, and maintained it; the venerable and irreplaceable Capt. Tom Golfinos, whose knowledge, memories, and stories weave an oral history of the past half century of developments in oceanographic science; and numerous full-time crew over the years, including David Brenha and John Rodrigues, who made the 2017 cruise possible. In spirit, if not by name, I would recognize the pioneering scientists who pushed the boundaries of oceanic exploration, inspiring the generations of scientists who followed them. These people and others made my time aboard *FLIP* possible—my time to bob above the ocean, watch the waves, and whoop as they passed—all without so much as a jostle or a wobble in my feet.

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▶ Read the article at bit.ly/Eos-FLIP

Australia's Unfolding Geoscience Malady

In July, the Australian geoscience community was shocked to learn that the globally recognized School of Earth and Planetary Science at Macquarie University in Sydney had been culled as part of the university's efforts to deal with pandemic-related revenue losses. This was the latest blow after a prolonged, nearly 2-year downsizing process during which 18 of the 21 academics who worked at the school were let go and, with them, Macquarie's ability to provide a well-rounded geoscience education. In the wake of this purge, the three remaining staff were left to bear what remains of the teaching load.

Unfortunately, this was not an isolated event. A string of mergers, cutbacks, and closures have hit geoscience departments across Australia in response to the recent financial pressures and low undergraduate enrollment numbers. The Australian National University Research School of Earth Sciences in Canberra made drastic cuts in December 2020, including massively reducing its operating budget and laying off 20 permanent staff members, plus additional contract employees. This layoff resulted in reduced levels of technical support across the entire school, the closure of its renowned mechanical workshop, and a major reduction in the research capability of the world's first SHRIMP (Sensitive High-Resolution Ion Microprobe) mass spectrometer laboratory, responsible for dating many of the oldest known Earth and extraterrestrial materials yet discovered.

Meanwhile, at the University of Newcastle, the geology major was dropped completely. In total, seven of the 21 Australian geoscience departments have been hit with substantive reductions in staffing and curriculum offerings in the past few years, and many others have suffered smaller reductions.

Although faults in Australian geoscience education predate COVID-19, the significant financial pressure inflicted upon Australia's universities as a result has catalyzed its rapid fragmentation. More casualties are likely to come as the Australian university sector is forecast to lose up to AU$19 billion (US$13.7 billion) between 2020 and 2023 because of the collapse of international student revenue. The federal government's refusal to financially back the university sector has forced institutions across the country to consolidate their educational offerings to those that generate the greatest profit. In 2020, 17,300 university jobs and AU$1.8 billion (4.9% of 2019 revenue) were lost across Australia, with a further 5.5% drop estimated for 2021. Research-related staff have been particularly hard hit, with women, early-career researchers, and recent graduates disproportionately affected. A 2020 federal decision to cut funding for Earth and environmental science courses by 29% has only compounded the situation, setting the sights of financially strapped universities looking to cut overhead squarely on the backs of geoscience departments.

The loss of these geoscience resources could not come at a worse time. Australia faces unprecedented environmental and energy challenges while simultaneously trying to revitalize an economy stunted by the COVID-19 pandemic. To tackle these challenges and ensure a sustainable and prosperous future, Australia needs the very geoscience expert community currently being diminished.

Geoscience, as the interface between humanity and Earth, is essential to tackling climate change and will aid in the economic recovery from COVID-19. The United Nations (UN) and the World Bank have championed geoscience as critical to reaching the UN's Sustainable Development Goals, disaster risk reduction, and achieving the goals of the Paris Agreement (e.g., clean energy technologies will greatly increase the demand for critical minerals).

What, then, has led Australia to jeopardize its ability to respond to these challenges by making deep staffing cuts and closing entire geoscience programs? What measures can be taken to save Australia's geoscience? And what implications does this have for the international geoscience community?

Broadening and Refocusing the Geoscience Narrative

Even before the COVID-19 pandemic, student enrollment in geoscience majors was in decline across Australia, despite increasing demand from diverse geoscience industry sectors. Although undergraduate enrollment appears anecdotally to be bouncing back in Western Australia following a post-2016 revival of the mining industry largely based there, student numbers in southeastern geoscience departments have not rebounded sufficiently to ensure their viability. The problem is that many people in the more urbanized southeastern states and territories view mining as the only career option for someone who pursues geology studies, an industry they understand to be detrimental to the environment.

This enrollment crisis extends beyond the shores of Australia.

The United Kingdom has also seen a progressive decline in undergraduate geoscience enrollment since 2016. It has been attributed to a parallel reduction in geology course offerings in primary and secondary schools. Geoscience enrollment has similarly collapsed in the United States over the past 5 years, a trend that predates the 2019–2021 shrinkage of employment prospects in the U.S. petroleum, mining, and geological engineering industries. These numbers are all made more complicated by the pandemic, including challenges in charting enrollment during virtual learning.

Thus, a global recasting of the geoscience narrative as a mechanism for meeting the challenges of science and society is needed to better reflect the true merit and breadth of its disciplinary applications.

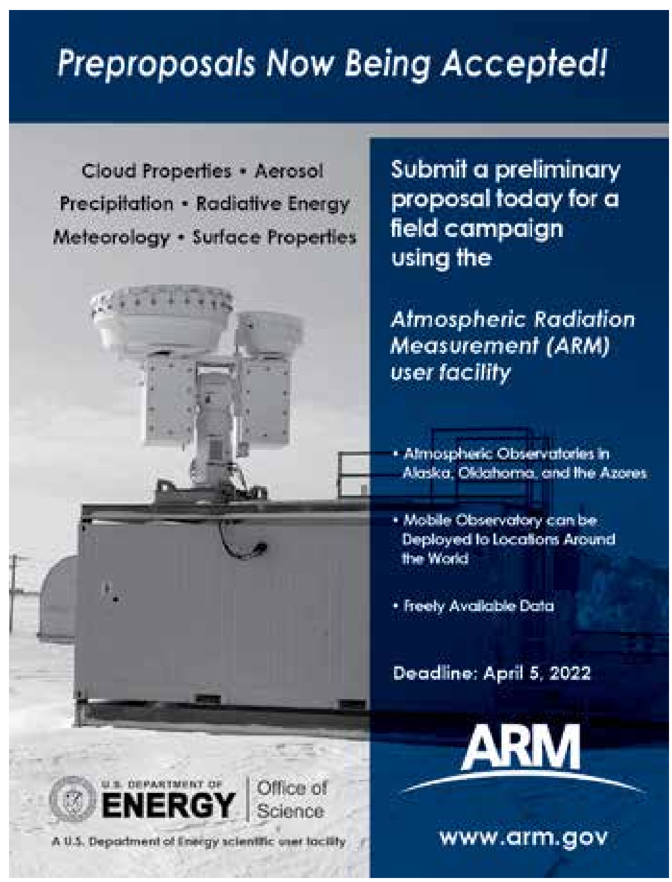
If we're going to convince young people that a geoscience education can lead to rewarding careers, we need to remold geoscience curricula so they align with contemporary student values. First, it must be made clear that contrary to many inaccurate public perceptions, the expertise and capabilities of the mining and petroleum industries will play a fundamental role in the global fight against climate change. Simply put, without meeting the fivefold increase in demand for critical minerals and sequestering 190 billion metric tons of carbon dioxide into sedimentary basins, we will fail to reach the Paris Agreement's carbon neutrality targets. However, economic geology courses should be accompanied by interdisciplinary lessons on environmental and mining ethics, which could form a more substantive component of classes on Earth resources.

Meeting the geoscience labor force needs of national and global communities must therefore become a strategic imperative for our universities.

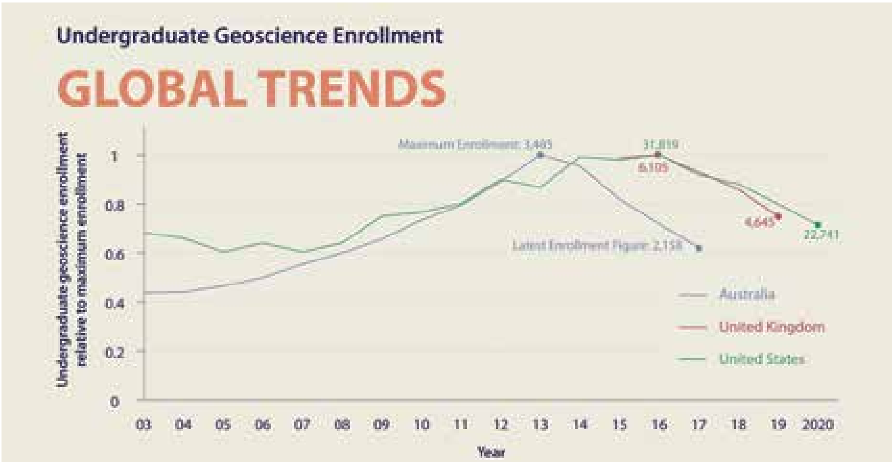
While maintaining core geoscience education and pursuing fundamental research, broader societal applications should also be incorporated into our curricula, including subjects on sustainability, water resources management, geoengineering, and the mitigation of natural and anthropogenic hazards. These are just a few ideas for rebranding the discipline to accommodate the cultural differences between those who want to pursue employment in the geological resources sector and those who do not.

This adaptation of geoscience curricula for a new era must involve substantive change, not simply be lip service to creating a more progressive career tract. In at least one high-profile case in the United States, small changes to geoscience syllabi were insufficient to attract students, so the university is now attempting a full overhaul of the Earth science curriculum to focus on preparing students to meet the pressing challenges of today.

What is clear, however, is that in many places, the current model is not attracting enough students for geoscience departments to remain viable in a financially weakened university sector. A community-wide dialogue is thus needed to develop a revived and unified geoscience education narrative that captures the imagination of young minds.



Opposite: iStock.com/VMJones



Undergraduate geoscience enrollment trends in Australia, the United States, and the United Kingdom since 2003. National enrollment data are normalized to the maximum enrollment for each country during the recorded time span. Although national undergraduate enrollment data for geoscience subjects are not yet available post-2017 for Australia or after 2019 for the United Kingdom, the downward trends in student numbers are expected to be exacerbated by the COVID-19 pandemic. Data sources are the Australian Geoscience Council, the American Geosciences Institute, and the U.K. Higher Education Statistics Agency (HESA). HESA undergraduate geoscience enrollment data for the United Kingdom are unavailable prior to the 2014–2015 academic year.

National Strategies for Geoscience Education and Research

Perhaps more than any other developed nation, Australia's wealth and prosperity depend on its geoscience expertise. This year alone, the country's mineral and energy resources sector is forecast to generate AU$296 billion (US$214 billion) in export earnings (~10% of gross domestic product) and will no doubt be key to powering Australia's recovery from the tumultuous economics of the COVID-19 era. The nation's ability to sustainably secure food, energy, and water is also reliant on the capacity of its geoscientists to discover, manage, and responsibly use its natural resources.

It is therefore in the government's own best interest to preserve its geoscience capacity. Australia needs a national strategy for geoscience education and research to temper the fiscal decisions of universities and ensure a future geoscience workforce. Previous programs designed to build national capacity, such as the Australian Mathematical Sciences Institute and the Minerals Tertiary Education Council (MTEC), were greatly successful in drawing increased enrollment when they were established over a decade ago. Indeed, the MTEC program contained many elements that could be implemented again today, with industry-funded teaching positions in critical geoscience disciplines created at several universities across the country, development of aligned national geoscience curricula, and funding travel for students to visit and study at other hubs across the country.

With new investment aligned to a national geoscience education strategy, teaching hubs across several universities could be identified and developed in areas of strength and strategic importance, such as renewable energy and critical mineral exploration, applied geophysics, water resources management, carbon sequestration, and geohazard mitigation.

David Cohen, president of the Australian Geoscience Council, recently advocated for such a national geoscience professional development system. Cohen argued for a partnership between industry, government, universities, and professional societies so that the system can deepen the skills of existing geoscientists while simultaneously providing a pathway for scientists from other fields to transition into the discipline.

When developing strategies to bolster its geoscience capacity, Australia might also look to the United Kingdom. In response to diminishing geoscience enrollment there, the Geological Society of London and University Geoscience UK have developed strategic aims to reinvigorate undergraduate-level geoscience education. In them, they lay out a multifaceted action plan for revamping geoscience education, funding, marketing, and diversity across a wide range of stakeholders to avoid the looming skills shortage. Addressing the geoscience maladies of Australia will require a similarly comprehensive strategy to be formulated and implemented by an alliance of geoscience departments, academic and professional societies, research infrastructure providers, industry advocates, and policymakers.

Saving Geoscience

Ensuring a sustainable and prosperous future, both in Australia and abroad, will require saving and empowering the geoscience community. Although geoscience departments produce relatively few graduates each year compared with other STEM (science, technology, engineering, and mathematics) disciplines with which they compete for university funding, they are, nevertheless, required to produce the skilled geoscientists demanded across a variety of industries critical to societal well-being. Meeting the geoscience labor force needs of national and global communities must therefore become a strategic imperative for our universities.

To do this, national strategies involving geoscience, university, industry, and government stakeholders are needed that rebrand geoscience in line with contemporary student values, align secondary school curricula to teach geoscience in the context of societal betterment, and develop and fund nationally coordinated university research and education programs in areas of community priority.

Acknowledgments

We acknowledge Mike Sandiford, Olivier Allard, Alan Collins, Annette George, and Jonathan Palmer for their informative input and suggestions.

▶ Read the article at bit.ly/Eos-geoscience-malady

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Reframing Funding Strategies to Build Reciprocity

The Sun rises beyond the summit of Mauna Kea, which is held sacred by Native Hawaiians. Credit: Anish Patel, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

University education and academic systems in the United States are permeated by a legacy of colonization of Indigenous Peoples. The Morrill Land-Grant Acts, enacted in 1862 and 1890, resulted in the dispossession and sale of more than 40,000 square kilometers (10 million acres) of Indigenous lands, providing financial security to universities across the country in the name of educating students and promoting economic development [*McCoy et al.*, 2021]. This colonization constituted attacks on people and land and was accomplished through purposeful misrepresentations of Indigenous cosmologies [*Watts*, 2013].

Western knowledge and science have long benefited from colonization of Indigenous Peoples through the continued exploitation of their lands and knowledge [*Tuhiwai Smith,* 2012]. In today's Western scientific establishment, this exploitation extends to the devaluing of work done by Indigenous community members who assist academic researchers. Together with other extractive behaviors, this devaluation erodes trust among Indigenous Peoples toward Western scientific traditions.

To improve relationships and engagement with Indigenous communities, scientists must recognize the limitations and failings of our current academic and research systems. The science community is making significant progress through grassroots efforts. Now it is time for academic, federal, and industry leadership to demonstrate their commitment to advancing justice, equity, diversity, and inclusion in the geosciences [*Ali et al.*, 2021; *Morris*, 2021].

This manaʻo is the product of my observations and experiences as a kanaka Ph.D. student in the geosciences. It follows in the footsteps of many past and ongoing conversations by and with mentors and colleagues [e.g., *Trask*, 1992]. I call for changes in research funding systems so they value equitable relationships with communities; acknowledge, in the grant process, the kuleana and timelines required to build relationships and pursue research and broader impacts in Indigenous communities; and enforce accountability from the highest levels within academia to encourage best practices as common practices in research.

Who Bears the Burden of Broader Impacts?

Building relationships with Indigenous communities where research is conducted requires substantial labor. This labor is typically unpaid and often falls to early-career researchers, especially faculty and graduate students from these communities [*Kimmerer*, 2013; *Kearns*, 2021]. As a kanaka graduate student at the University of Hawaiʻi at Mānoa, I am often asked and expected to volunteer in the relationship-building process with the local Native Hawaiian community. This process involves developing professional and personal connections with community members over months to years. And because I am a member of this community, my behavior and reputation hold many personal consequences that I—and my ʻohana—cannot walk away from. Despite these expectations, Indigenous scientists are often told by academic, federal, and industry leaders that this work is not valued as rigorous research—that it's "not a good use of my time" in the academic setting compared with producing publications and giving conference presentations. This added and undervalued labor creates hurdles for Indigenous scholars to overcome.

Community members are often also asked to provide expertise, time, and energy on behalf of scientists [*Gewin*, 2021]. These individuals sometimes go without pay or even recognition of their contributions and are otherwise left out of the research process because they are not seen as members of the research team. Academic researchers who do not recognize intellectual property rights and acknowledge contributions and efforts from Indigenous communities fail to honor the ethical guideline of free, prior, and informed consent, which "works to ensure that knowledge holders within Indigenous communities retain informed decision-making authority regarding their participation in the research process" [*David-Chavez and Gavin*, 2018].

Broader impact statements and plans are now required for many research proposals. Researchers often submit plans that may sound ethical and broadly beneficial but cover a wide range of engagement activities that may not be feasible given funding and research timelines. Do such broader impacts actually consider community practices and meet the needs of community members? And do funding agencies hold grantees accountable for following through with their plans? Without explicit metrics gauging outcomes of broader impacts, it is impossible to evaluate their effectiveness, let alone how Western researchers are fulfilling responsibilities of reciprocity [*Nadkarni and Stasch*, 2013]. Meanwhile, is anyone holding the funders themselves accountable for ensuring that engagement efforts are respectful?

There have been repeated calls for federal organizations like the National Science Foundation (NSF) and NASA to hold themselves and the researchers they support accountable for the impacts their work has on local communities and environments. One way to create this accountability is to change how our academic and funding systems are structured so they better value relationship building and broader impacts on communities. Funding timelines should realistically reflect the needs of the relationship-building process and provide support for Indigenous communities that provide unpaid labor to the scientific community. Without this accountability, the same mistreatments will continue to occur, and scientists will create animosity and mistrust rather than the equitable relationships that are necessary for effective and ethical work with communities.

Enacting Accountability in Community Engagement

Although some funding programs that promote community-based research and relationship building, such as NSF's Established Program to Stimulate Competitive Research (EPSCoR) and Geoscience Opportunities for Leadership in Diversity-Expanding the Network (GOLD-EN), this work is not valued across all funding systems and academia. Until it is, ethical research practices will not be given full merit in hiring, tenure, and promotion processes. In some cases, proposing community-focused work can even be detrimental to researchers because it may not be seen as impactful research in the scientific community [*Gewin*, 2021].

Relationship building is an increasingly important aspect of research for all scientists, but it is inherently a kuleana for Indigenous scholars: There is no way for us *not* to do it. When academic hiring and promotion processes do not value relational work, Indigenous scholars and communities are undervalued for their contributions.

Currently, there are few incentives for researchers to take time to build relationships before writing grant proposals or to continue relationships beyond a grant's expiration date. However, if relationship building were valued in academia—and incentivized by funding agencies—researchers would, in turn, be prompted to also value equitable relationships and collaborations with the communities in which they work. How, then, do we start to bring about this change?

The Thirty Meter Telescope protests mark a significant moment in our history, when kanaka stood up and said enough is enough, that scientists must understand how scientific advancements have affected communities around the world.

All too often, when researchers do work within communities, community members are exploited for their knowledge, not credited for their contributions, and not given authority over the research process [*David-Chavez and Gavin*, 2018]. Community leaders and organizations are seen as volunteer outside collaborators who can be called upon when needed—and thus are often kept in the dark about research plans, methodologies, and final outcomes or products.

Although it takes time to build trust with communities, it is scientists' kuleana to ensure that we follow proper protocols of engagement. The United Nations Declaration on the Rights of Indigenous Peoples outlines the bare minimum of expectations for how we should be engaging. Among other points, these protocols guarantee Indigenous Peoples the right to free and informed consent. In some cases, discussions between researchers and communities may lead to the outcome that no research is consented to and therefore none can be conducted—an outcome that researchers must respect and value as part of rebuilding trust.

In the relationship-building process, honoring Indigenous Knowledge systems and cultural practices is paramount [*Kahanamoku et al.*, 2020]. To promote respectful and reciprocal engagement with local communities, targeted funding in grants for relationship building should be provided to both the communities and researchers. This funding would provide resources and time to support mutually beneficial and respectful interactions that focus not only on producing meaningful research but also on the needs and concerns of community leaders, including questions of data sovereignty, ownership, and access as well as coauthorship or co-review of project outcomes.

Encouraging Best Practices in Community-Driven Research

The development of the Thirty Meter Telescope (TMT) on the sacred land of Mauna Kea is one example of how the geosciences have perpetuated extractive behaviors in Hawaii and elsewhere. Despite misconceptions, protests by Native Hawaiians opposed to the TMT are not rooted in antiscience perspectives (although they do reflect erosion of trust in the Western scientific establishment); rather, they arose because extractive practices are detrimental to the health and cultural prosperity of Native Hawaiians.

The historic "lack of transparency and egregious mismanagement of Mauna Kea," as *Alegado* [2019] described it, highlight important aspects missing from science collaborations, especially respect for Indigenous Peoples' cultural integrity and the process of building relationships. The TMT protests mark a significant moment in our history, when kanaka stood up and said enough is enough, that scientists must understand the history of how scientific advancements have affected communities around the world, and that they must learn from earlier mistakes to change their approaches.

There are resources that can help develop relationship-building and -sustaining skills, as I have learned over the past few years. The Kūlana Noiʻi outlines best practices and guiding questions regarding respect, reciprocity, self-awareness and capacity, communication, maintaining a long-term focus, community engagement and co-review, knowledge ownership and access, and accountability. The volume *Kanaka ʻŌiwi Methodologies: Moʻolelo and Metaphor* includes a collection of methodology-focused essays from kanaka scholars in varying disciplines. The authors describe how they use these methodologies to guide and inform their research process and to gain a deeper understanding of language and culture, allowing for positive social changes.

Some organizations, such as the Rising Voices Center for Indigenous and Earth Sciences at the National Center for Atmospheric Research, hold space for the coming together of Western and Indigenous scientists. Among other contributions, the Rising Voices Center has acknowledged that recognizing Indigenous community needs in research, including data sovereignty, coauthorship, and accountability, has been an important step forward in developing scientific collaborations. At the Indigenous Geography website, researchers can find resources about collaborative research methodologies from around the world that can help to start the relationship-building process with Indigenous communities.

Raising Our Standards

As a kanaka scholar, I am required to follow proper protocols and procedures in my academic research: take time to talk with community members, meet frequently to share results, and conduct my work in a pono way. As a researcher, I am held to the highest standards of quality and ethics when reporting my research: sharing quality assurance and quality control information, calculating analytical errors in data sets, and detailing my research methodologies. Why are similarly high standards not applied when communicating and collaborating with Indigenous communities? It is not only our kuleana as scientists to hold ourselves accountable, but it is also incumbent upon funding agencies to hold themselves and the scientists they support to the highest standards when engaging Indigenous communities.

As we move down the path of knowledge together, empowering Indigenous Knowledges, Peoples, and cultures to remain sovereign is essential. Updating funding systems is just one step the scientific community can take to value equitable relationships with communities and the processes needed to build those relationships. This change will allow for more accountability across all levels of academia and will result in science that is mutually beneficial to, and respectful of, everyone involved.

Acknowledgments

The author is grateful for input and feedback provided by Rosie Alegado, Kristen Luna Aponte, Carolyn Brinkworth, Aurora Kagawa-Viviani, Sara Kahanamoku, Kaiwipuni Lipe, and Katy Putsavage.

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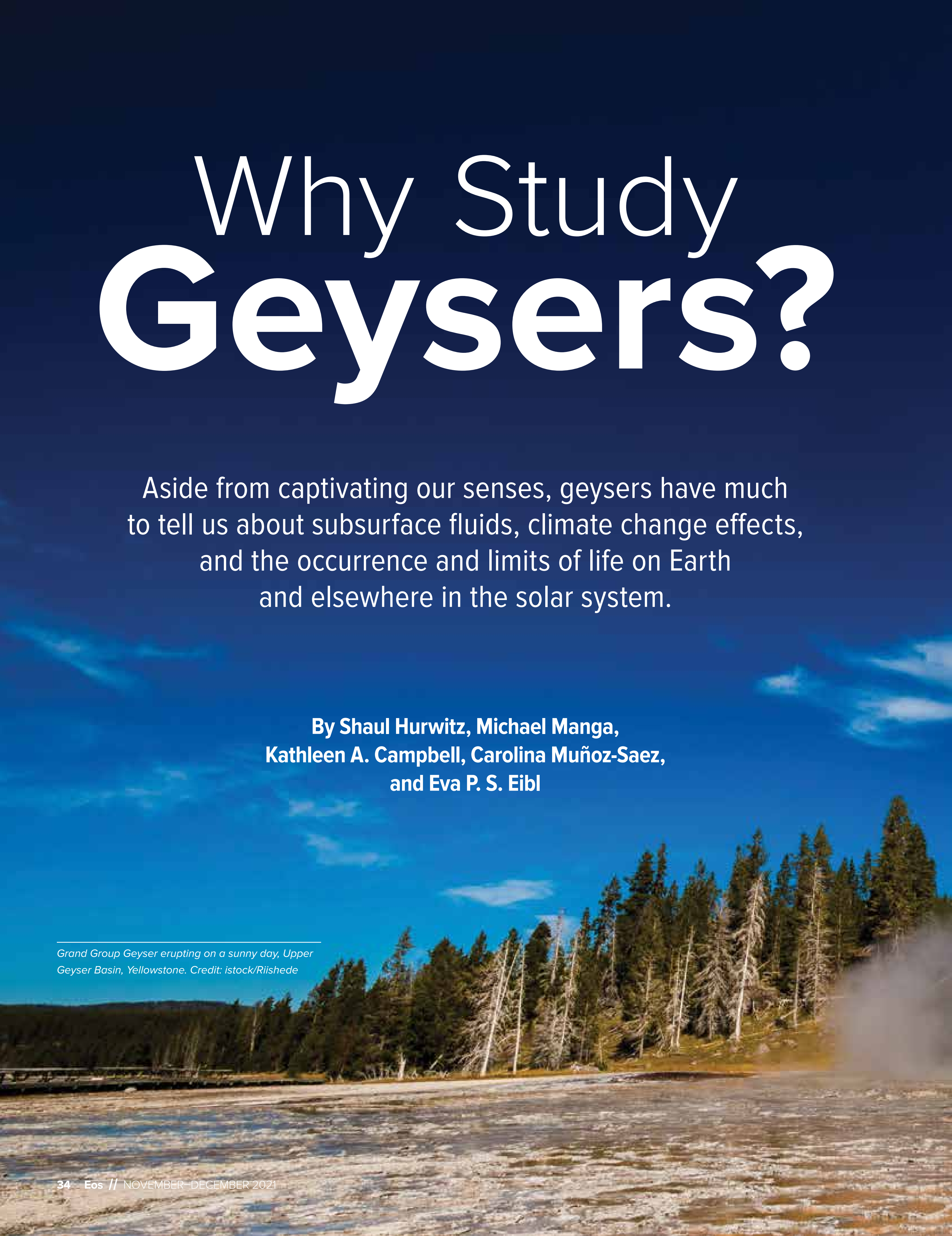
Why Study **Geysers?**

Aside from captivating our senses, geysers have much to tell us about subsurface fluids, climate change effects, and the occurrence and limits of life on Earth and elsewhere in the solar system.

By Shaul Hurwitz, Michael Manga, Kathleen A. Campbell, Carolina Muñoz-Saez, and Eva P. S. Eibl



Grand Group Geyser erupting on a sunny day, Upper Geyser Basin, Yellowstone. Credit: istock/Riishede

Each year, millions of tourists visit geysers around the world, marveling at the jets of water spouting high into the air from subterranean reservoirs. Fascination with these rare features is nothing new, of course: Written records of their occurrence date back to the 13th century at least, and for more than 2 centuries, scientists have been improving our understanding of Earth's geysers.

The English word *geyser* originates from *geysir*, a name given by Icelanders in the 17th century to intermittently discharging hot springs. The name descends from the verb *gjósa*, which means to gush or erupt. Natural geysers are rare—fewer than a thousand exist today worldwide, and only a handful of fossil examples are known from the geological record. About half of Earth's geysers are located in Yellowstone National Park in the United States. Other large geyser fields include the Valley of Geysers in the Kamchatka Peninsula of Russia, El Tatio in Chile, and Geyser Flat at Te Puia, Rotorua, in New Zealand.

In 1846, French mineralogist Alfred Des Cloizeaux and German chemist Robert Wilhelm Bunsen formulated an early model to explain geyser eruptions based on field measurements of temperature, chemistry, and circulation and eruption patterns at Geysir in Iceland. Since then,

Eruption processes of geysers, which can be driven by geothermal heating and the formation of vapor bubbles, are akin to those operating in volcanoes.

scientific knowledge of geysers has advanced significantly [*Hurwitz and Manga*, 2017], providing valuable insights into volcanic processes, the origin and environmental limits of life on Earth (and potentially elsewhere, including on Mars), and similar geysers on icy outer solar system satellites. Demonstrating these connections, geologist and planetary scientist Susan Kieffer wrote the following in a perspective on her research career: "[M]y initial idea of studying Old Faithful geyser as a volcanic analog [*sic*] led me to work not only on the dynamics of eruption of Mount St. Helens in 1980 but also on geysers erupting on Io (a fiery satellite of Jupiter), Triton (a frigid satellite of Neptune), and Enceladus (an active satellite of Saturn)."

Continuing research into the inner workings of geysers will help us further understand and protect these natural wonders and will reveal additional insights about volcanism on and off Earth.

An array of instruments (foreground) measures seismic tremor around geysers at El Tatio in Chile. Credit: Shaul Hurwitz, U.S. Geological Survey

Like Volcanoes, but More Accessible

Similar to volcanoes, geysers are transient features with periods of activity and dormancy. Geyser eruption patterns can change following large earthquakes, shifts in climate, and variations in the geometry of their conduits and subsurface reservoirs. Eruption processes of geysers, which can be driven by geothermal heating and the formation of vapor bubbles, are also akin to those operating in volcanoes.

The model developed by Des Cloizeaux and Bunsen showed that as water rises toward the surface and pressure decreases, boiling forms bubbles. The liquid water containing the bubbles further lowers the density and pressure of the mixture. Decreasing pressure similarly causes changes in magma that underpin key volcanic processes, such as melt generation in the mantle and the formation of bubbles in magma that drive eruptions.

Because geysers have smaller eruptions and erupt more frequently than volcanoes, they provide useful natural laboratories to study eruption processes and test new monitoring technologies. Volcanic eruptions are sometimes preceded by magma movement that is difficult to monitor because of the large spatial scales and long timescales involved. In contrast, measurements of fluid movement, for example, can be made relatively easily through many geyser eruption cycles, providing data that can be used to improve the interpretation of volcanic phenomena. Measurements and video observations can also be collected within the conduits of active geysers—a feat impossible at active volcanoes.

Signals such as seismic tremor—sustained ground vibrations that are common prior to and during volcanic and geyser eruptions—can be very informative for monitoring subsurface processes at active volcanoes and geysers. Tremor in volcanoes can last for days, weeks, or even longer leading up to volcanic eruptions [*Chouet and Matoza*, 2013]. Tremor may be caused by degassing of magma and by the movement of fluids within a volcanic edifice. However, identifying fluid types (gas, liquid water, magma) and the processes responsible for episodes of tremor is challenging because of the geometric complexities and sizes of volcanic systems.

Seismometers deployed around the iconic Old Faithful and Lone Star geysers in

Yellowstone have detected tremor caused by continuous bursts of rising steam bubbles, analogous to bubbles forming and bursting in a teakettle. Thus, by analogy, such measurements of tremor in geyser systems can help elucidate processes that generate volcanic tremor.

Tracking tremor signals in time and space using dense arrays of seismometers also has illuminated the subsurface structure of volcanoes and geysers [*Eibl et al.*, 2021; *Wu et al.*, 2019]. The locations of tremor sources around Strokkur Geyser in Iceland, and Old Faithful, Lone Star, and Steamboat in Yellowstone, for example, indicate that these geysers' reservoirs are not located directly beneath their vents. Tilting of the ground surface around Lone Star Geyser and a geyser at El Tatio, as well as video observations in the conduits of geysers in Kamchatka, also indicate reservoirs that are not aligned below the geysers' vents. This type of reservoir, in which liquid and steam bubbles accumulate and pressure builds prior to an eruption, is called a bubble trap and might be a common feature of many geysers [*Eibl et al.*, 2021].

Laboratory experiments of geysers have shown how heat and mass transfer between laterally offset reservoirs and conduits control eruption patterns [*Rudolph et al.*, 2018]. Geophysical imaging has similarly revealed that although most volcanic vents are located directly above their magma reservoirs, many reservoirs are laterally offset from their associated volcanic edifices [*Lerner et al.*, 2020].

A striking example of an offset magma reservoir was highlighted in a 1968 study of the Great Eruption of 1912 in Alaska [*Curtis*, 1968], in which magma erupted from Novarupta volcano, but collapse occurred some 10 kilometers away at Mount Katmai, where most of the magma that erupted at Novarupta had been stored. Mapping of such laterally offset magma storage systems, as well as detailed physical knowledge of how they work as gleaned from studies of and experiments with geysers, may help scientists design better volcano monitoring networks.

Carolina Muñoz-Saez inserts pressure and temperature sensors into a geyser conduit at El Tatio in northern Chile. Seismometers that measured seismic tremor throughout many eruption cycles are visible in the background. These experiments were conducted in coordination with the communities of Caspana and Toconce. Credit: Max Rudolph, University of California, Davis

Earth Tides, Earthquakes, and Climate Change

Eruptions at geysers and volcanoes are controlled by delicate balances in heat supply and gas and fluid flows within their systems, and by the tortuous pathways that liquid water, steam, and magma take to the surface—balances that can be affected by external forces. Documenting whether geysers and volcanoes respond to tides and earthquakes provides opportunities to quantify their sensitivity to changes in physical stress in the subsurface and to help evaluate whether they are poised to erupt [*Seropian et al.*, 2021].

Past studies have suggested, on the basis of statistical correlations, that small forces exerted by Earth tides can trigger volcanic eruptions. However, statistical tests of tidal influence on volcanic eruptions are limited because of the rarity of eruptions from a single volcano. In contrast, the thousands of geyser eruptions that occur annually form a much broader sample pool on which to base statistical tests. One such evaluation uncovered a lack of correlation between Earth tides and the intervals between geyser eruptions, a finding that suggests that a correlation between Earth tides and volcanic eruptions is also unlikely.

Although tides might not affect geyser eruptions, regional and even very distant large earthquakes can. Written accounts document renewed activity of Geysir following large earthquakes in southern Iceland in 1294. In Yellowstone, some geysers stopped erupting whereas others started erupting, after the magnitude 7.3 Hebgen Lake earthquake in Montana in 1959. The magnitude 7.9 Denali earthquake in Alaska in 2002 affected eruptions of some Yellowstone geysers 3,000 kilometers away.

Earthquakes can also promote volcanic unrest and eruptions. Establishing causal relations between earthquakes and eruptions is challenging because few active volcanoes occur in any given area, and changes in the subsurface can take longer to manifest as an eruption. However, geysers erupt more frequently than volcanoes, which again points to the utility of studying geysers as volcanic analogues.

Precipitation trends and climate changes can affect geysers as well. Eruption intervals at Old Faithful Geyser have changed in the past, and it even ceased erupting in the 13th and 14th centuries because of a severe drought. How often geysers erupt may also change in response to seasonal and decadal changes in precipitation, which affect the supply of groundwater that feeds the eruptions.

Volcanoes also display slight seasonal patterns in their eruptions, and they respond to changing climate. As air temperatures warm, for example, glaciers covering volcanoes melt, which in turn reduces pressure on underlying magma. Pressure reduction causes gas bubbles to form, and the buoyant mixture of magma and bubbles is then more primed for eruption.

On longer timescales, rates of volcanism vary over glacial cycles, with more eruptions and larger volumes of magma erupted as glaciers retreat. In line with this observation, we know from dating sinter deposits and from geologic mapping that most geyser fields were inactive during Earth's last glacial period (which ended between ~20,000 and 12,000 years ago) when they were covered by ice [*Hurwitz and Manga*, 2017].

New sound and visual approaches developed to convey complex patterns in geyser systems may help identify relationships between volcanic signals that might otherwise be overlooked.

Origins and Limits of Life on Earth and Mars

Sinter deposits form when hot water erupting from geysers cools and evaporates rapidly at the surface, causing dissolved silica to precipitate as opaline or amorphous (noncrystalline) solids. High-temperature, vent-related sinter that forms in surge and splash zones around or near erupting geysers is termed geyserite. Around geysers and in downslope pools and discharge channels, the complex sedimentary structures preserved in sinter reflect physical, chemical, and biological processes occurring in hot spring subenvironments. For example, sinter textures produced in hot spring fluid outflows record temperature and pH gradients across a given geothermal field, from vents to discharge channels to pools, and from terraces to marsh settings.

Sinter typically entombs both biotic (e.g., microbes, plants, animals) and abiotic (e.g., weathered sinter fragments, volcanic ash, detritus) materials. Geyserite, in particular, serves as an archive of conditions in Earth's hottest environment on land (up to about 100°C) and of extreme thermophilic (high temperature-adapted) life therein [*Campbell et al.*, 2015].

Research on modern hot springs suggests not only that they can host extant life, but also that extended hydration and dehydration cycles in geyser outflow channels can give rise to prebiotic molecular systems that display fundamental properties of biology, such as enclosed, cell-like structures composed of lipids and polymers [*Damer and Deamer*, 2020]. This observation hints at a possible role for geysers in the origin of life on Earth billions of years ago. Indeed, inferred geyserite deposits associated with rocks containing microbial biosignatures have recently been reported in approximately 3.5-billion-year-old hydrothermal sedimentary deposits in Western Australia [*Djokic et al.*, 2017].

On Mars, silica-rich deposits detected by the Spirit rover amid Columbia Hills in Gusev Crater closely resemble fingerlike sinter textures on Earth. This site was proposed as a landing site for the NASA Mars 2020 mission, which will cache samples for eventual return to Earth. Although the Perseverance rover was instead sent to explore deltaic deposits in Jezero Crater, the digitate silica structures at Columbia Hills remain as biosignature candidates that may one day be collected and brought to Earth for in-depth verification of their origin. Therefore, sinters remain a key target in the search for ancient life on Mars, particularly from the time in its history when volcanoes and liquid water were active at the surface—about the same time that life was taking hold in hot water here on Earth.

A recent geyserite deposit from northern Waiotapu, in New Zealand's Taupo Volcanic Zone, shows fingerlike formations. Similar formations have been found in silica-rich deposits on Mars. Credit: Kathleen A. Campbell, University of Auckland

In addition to benefiting our understanding of what constitutes life and where it can thrive, advanced biotechnology has also benefited from geyser studies. In 1967, microbiologist Thomas Brock and his student Hudson Freeze isolated the bacterium *Thermus aquaticus* from the hot waters of Yellowstone's geyser basins. Later, biochemist Kary Mullis identified an enzyme, named Taq polymerase, in a sample of *T. aquaticus* that was found to replicate strands of DNA in the high temperatures at which most enzymes do not survive. This discovery formed the basis for developing the revolutionary polymerase chain reaction (PCR) technique in the 1980s (for which Mullis shared the 1993 Nobel Prize in Chemistry). PCR is now the workhorse method used in biology and medical research to make millions of copies of DNA for various applications, such as genetic and forensic testing. Recently, PCR also became widely used for COVID-19 testing.

Exploring for Energy and Mineral Deposits

Sinter deposits can also inform exploration for geothermal energy, helping locate resources, as well as for mineral deposits. Whereas currently active hydrothermal systems provide energy for electricity generation, industry, and agriculture, giant fossil hydrothermal systems host many of the world's most productive precious metal mining operations [*Garden et al.*, 2020]. Such epithermal ore deposits form in the shallow subsurface beneath geothermal fields as high-temperature fluids—both magmatic and meteoric in origin—gradually deposit valuable metals including gold, silver, copper, and lithium.

Geyserites form at the surface emission points of rising hot fluids tapped from deep reservoirs and can point to completely concealed subsurface ore deposits [*Leary et al.*, 2016], thus informing exploration for mineral resources; they may also contain traces of precious metals themselves.

Geysers in the Solar System

Studies of physical processes in easily observable geysers on Earth can also guide and constrain models proposed to explain eruptions elsewhere in our solar system. The geysers of the icy outer solar system satellites Enceladus (Saturn), Triton (Neptune), and Europa (Jupiter) are similar to Earth's geysers in that changes of state of materials (e.g., melting and vaporization) drive mixtures of solids and gases to erupt episodically.

At the south pole of the ice-covered ocean world Enceladus, some 100 geysers erupt from four prominent fractures, delivering water from a habitable ocean into space and supplying ice particles to Saturn's E ring. At Triton, the largest of Neptune's 13 moons, NASA's Voyager 2 spacecraft detected surface temperatures of −235°C and geysers that erupt sublimated nitrogen gas. Whether eruptions currently occur on Europa remains debated.

As on Earth, studying physical controls on geyser location, longevity, and eruption intervals on these other worlds can improve our understanding of interactions between their interiors and their surface environments.

Visitors on a boardwalk watch an eruption of Grand Geyser in the Upper Geyser Basin of Yellowstone National Park in June 2012. Credit: Jim Peaco, National Park Service

Engaging the Public in Research and Conservation

Tourists and amateur enthusiasts are captivated by the views and sounds of geyser eruptions. These spectacular events also provide public showcases for curiosity-driven scientific research. For example, new sound and visual approaches developed to convey complex patterns in geyser systems could provide valuable educational tools and may also help identify relationships between volcanic signals—such as surface deformation and seismicity indicating preeruptive activity—that might otherwise be overlooked.

Characterizing the sources of thermal water feeding geyser eruptions and mapping the subsurface hydraulic connections between geyser fields and adjacent areas are needed to protect and preserve these natural wonders from human impacts. Geothermal energy production and hydroelectric dam siting have drowned or driven more than 100 geysers to extinction in New Zealand and Iceland, for example, and geyser eruptions completely ceased in Steamboat Springs and Beowawe in Nevada owing to exploitation of geothermal resources. In contrast, some dormant geysers in Rotorua, New Zealand, resumed erupting a few decades after geothermal extraction boreholes were shut down.

Geysers are curious and awe-inspiring natural phenomena, and they provide windows into a broad range of science questions. They deserve both our wonder and our protection.

Acknowledgments

We thank the communities and agencies that enabled research on land they own or manage (Amayras Communities of Caspana and Toconce in El Tatio, Chile; Environment Agency of Iceland for research near Strokkur; the Department of Conservation, Wai-O-Tapu Thermal Wonderland, the Ngati Tahu-Ngati Whaoa Runanga Trust, and Orakei Korako Geothermal Park and Cave in New Zealand; and the National Park Service in the United States for research in Yellowstone). We thank Wendy Stovall, Lauren Harrison, and Mara Reed for constructive reviews. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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Virtual Tours Through the Ice Using Everyday Tools

The Byrd Polar and Climate Research Center is training scientists to create immersive virtual field experiences of glaciers, sea ice, and snow.

BY KIRA HARRIS, KASEY KROK, RYAN HOLLISTER, AND JASON CERVENEC

In the Virtual Ice Explorer, visitors can launch a virtual tour of Kennicott Glacier and ride along with Earth scientist Lia Lajoie as she explores this feature in the Wrangell–St. Elias National Park and Preserve in Alaska. Credit: Byrd Polar and Climate Research Center


To snow pit

You know you are on to something special when researchers who have traveled to and experienced the wonder of some of the most remote places on Earth are captivated by a tool that takes them to these locales virtually.

Earth's cryosphere, including its ice sheets, ice caps, glaciers, sea ice, and permafrost, is undergoing stark changes as air temperatures continue to rise. Scientists who study these regions understand viscerally the scale and scope of these changes, but they encounter limitations in communicating their experiences and observations to the public. Digital learning tools and online scientific data repositories have greatly expanded over the past decade, but there are still few ways for the public to explore rapidly changing icy environments through a realistic platform that provides contextual information, supplemental media, and connections to data sets.

The Virtual Ice Explorer (VIE) aims to bring the public closer to these important places (bit.ly/virtual-ice-explorer). Developed by the Education and Outreach (E&O) team at the Byrd Polar and Climate Research Center in Ohio, VIE encourages informal learning about icy environments by immersing visitors in "choose your own adventure" tours. Click on the globe on the home page and head to, for example, the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition that intentionally froze its ship into Arctic sea ice for a year of observations last year. You'll land on the deck of the icebreaker R/V *Polarstern* overlooking the ice camp—no long voyage required. Next, you can visit scientists in action, sampling Arctic waters up to 1,000 meters below the ocean surface through a hole drilled in the ice. Or maybe you'd like to see how researchers spend their off-hours with a little snow soccer. These options offer visitors a glimpse into the daily lives of scientists in the field as they fill in the blanks about what researchers study in these extraordinary locations and why it matters to our understanding of the planet.

This ease of use in the field was an essential criterion if we were to ask scientists to carry the cameras along on expeditions.

DIY-ing the First VIE

VIE was originally conceived as a platform to display immersive tours for about a dozen glacial sites around the world, generated from digital elevation models draped with satellite imagery. Following setbacks caused by the quality of the virtual landscapes created from satellite data and challenging user experience, two opportunities allowed us to reenvision VIE: (1) the acquisition of rugged, easy-to-use field cameras and (2) our discovery of existing commercial software with which we could more easily create tours that had been painstakingly built with custom code. We also began involving researchers who visited these sites firsthand; their experiences turned out to be essential for our tour development.

Our team purchased a GoPro Fusion 360° camera by way of a generous donation to the Byrd Center. At the same time, Michael Loso, a geologist with the U.S. National Park Service, was planning to spend a field season at Kennicott Glacier in Alaska. Loso agreed to take the camera and capture footage. We shared his footage using a virtual reality (VR) headset during Byrd Center outreach events and with park visitors, and also collected feedback. We were particularly moved by a visitor who appreciated that the tour allowed them to explore a site that was otherwise inaccessible due to a physical disability.

These rugged, inexpensive, and relatively easy-to-use cameras come with their own software and have a multitude of third-party programs available. Researchers can set them up, hit record, and walk away to focus on their work. This ease of use in the field was an essential criterion if we were to ask scientists to carry the cameras along on expeditions. After capturing and rendering video using GoPro's software, we use tools like Adobe Premiere Pro for additional editing, Dashware for accessing location data, and Plotly's Chart Studio for graphing and hosting interactive data sets.

A workshop run by Ryan Hollister, a high school educator, during the 2019 Earth Educators' Rendezvous also led to tremendous advances in our team's ability to create VIE tours. Hollister showed off the immersive virtual field experience he created for the basalt Columns of the Giants in California and walked attendees through designing their own experiences. After collecting 24 panoramic images with a Nikon D750 camera, Hollister stitched them together to create a 360° image using Autopano Giga software. He then used 3DVista software to add an interactive overlay to the images that allowed users to move to different locations within a site, click on marked points of interest and read about them, and embed 3D models of rock samples. This software was originally designed for architects and real estate professionals to create virtual tours of buildings, so it seamlessly constructs the computer code underpinning the tours with landscapes. Today 3DVista caters to wider audiences, including educators, and it provides such services as live guided tours and hosting capabilities.

The 3DVista software allowed us to create glacial landscape tours that we had been building with customized computer code, but in far less time. Use of off-the-shelf software allowed us to spend more time collecting footage, creating compelling narratives, and testing a wider range of scene designs. In the future, we plan to use 3DVista's user-tested interface to train educators and researchers to create their own tours.

Getting Scientists Camera-Ready

The E&O team now trains Byrd Center researchers with the cameras on basic photography techniques and more specific 360° filming techniques to capture high-quality video for VIE and other outreach programs. We want researchers to illustrate the vast, unique landscapes in which they're working and to showcase engaging scenes from their day-to-day experiences. We train them to create compositions to fill a scene, such as the inclusion of people to provide scale and demonstrate the research process, and we encourage them to film all parts of the expedition, including the journey, their living conditions, and interactions with collaborators and local partners.

We also have conversations with expedition members on the nature of their research, the field site itself, the equipment that will be on-site, and the desired impact of our outreach so that we can coproduce a narrative that guides what they film. These training sessions help the E&O team consider unique content for each tour, such as maps of study sites, time-lapse series, information on samples and equipment, biographies of researchers, links to publications, and prominent messages that properly identify and give respect to the people and places shown.

This screen capture is from Byrd Polar and Climate Research Center's Virtual Ice Explorer tour called "Huascarán, Yungay, Peru," showing scientists at work on the 2019 Ice Core Paleoclimatology expedition to Mount Huascarán. Credit: Byrd Polar and Climate Research Center

A benefit of having researchers explore virtual tours of other sites before they embark on their journey is that it generates genuine enthusiasm to share their own experiences. Chris Gardner, a Byrd Center researcher, viewed a tour of ice core drilling on Mount Huascarán in Peru while preparing to lead an expedition to the Dry Valleys of Antarctica during the 2019–2020 field season. Once he saw what was possible, he met with the E&O team to develop a video capture plan. Importantly, Gardner involved his entire team in selecting shots, recording video, and contributing to the tour narrative.

Authors Kira Harris and Kasey Krok have participated in many of these training sessions as undergraduate interns on the E&O team. They found that these sessions offered opportunities for pivotal interpersonal interactions among group members, including undergraduate and graduate students, postdocs, and investigators. Students gained a better understanding of the science that researchers were carrying out, while getting an opportunity to share their sometimes more finely honed technical experience in video and photography.

High-Quality Tours With a Low Lift

As of this writing, the Byrd Center has created virtual field experiences for nine sites, thanks to collaboration with the National Park Service, the Ohio Department of Natural Resources, and the many scientists who filmed their field campaigns. Additional examples of virtual field experiences by other groups include VR Glaciers and Glaciated Landscapes by Des McDougall at the University of Worcester; The Hidden Worlds of the National Parks by the National Park Service; and immersive virtual field trips by Arizona State University. More are being developed all the time. At AGU's Fall Meeting 2020, for example, there were numerous oral sessions and posters highlighting the applications of virtual field experiences.

Our E&O team has published an instructional guide for educators and scientists to use to build their own virtual field experiences tailored to their initiatives, using the same workflow that we use (bit.ly/instructional-guide.) Ryan Hollister has several resources, including guides on the technical requirements for high-resolution tours, creating 3D models of rock samples, and how to use the Next Generation Science Standards to best adapt immersive virtual field experiences for all learners (bit.ly/hollister-resources.) Our team also continues to test new tour features that will increase user engagement, knowledge retention, and options for user interaction. Last year, while closed to the public due to the COVID-19 pandemic, we even created a virtual tour of the Byrd Center to continue reaching out to the thousands of individuals who typically visit our facility each year.

What's most exciting is that these virtual explorations allow individuals almost anywhere in the world—regardless of their wealth, abilities, or learning preferences—to experience new landscapes and engage with Earth science lessons. While you can get the best view of the tours on a VR headset, all you need is a modest Internet connection and a laptop, tablet, or smartphone. These tours can be developed to specifically put visitors into the role of scientist to observe the terrain and use the provided data to make evidence-based claims.

This virtual field access enables individuals of all ages to get a taste of field research, appreciate the daily work of scientists, and gain a deeper understanding of our rapidly changing natural world. Although nothing can truly replicate an in-person field experience, virtual tours can be used to enhance educational opportunities in cases where people would otherwise not have access to those experiences, such as in large introductory courses, socially distanced laboratory exercises, or locations that need protection from oversampling or ecotourism. We can't always bring people to the far reaches of the world, but we now have many tools to bring the vast world to each of us.

Create Your Own Virtual Field Experience

Start with the Byrd Center's instructional guide on their website, then collect the following:

- Record: GoPro MAX 360° waterproof VR camera
- Edit footage: Adobe Premiere Pro
- Add location data: Dashware
- Host videos to access in tour: Vimeo
- Add 3D objects: Sketchfab
- Add the virtual tour overlay: 3DVista

Acknowledgments

Funding for this project was provided by the National Science Foundation under award 1713537 and a contribution from ENGIE/Ohio State Energy Partners. We thank the MOSAiC expedition and the NSF Office of Polar Programs for their continued collaboration on this project.

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WATER WISDOM: THE INDIGENOUS SCIENTISTS WALKING IN TWO WORLDS

By Jane Palmer






Meet the international researchers who draw on both academic training and cultural experience to help Indigenous communities protect water, restore ecosystems, and sustain traditional resources.





On the opener: Hydrologists from Indigenous communities move between two worlds. Page 44: (top) Volunteers remove invasive grass and plant Native Hawaiian sweet potato at Waiale'e on the north shore of Oahu in March 2021 (Credit: Vance Farrant). (bottom) Skolt Sámi fisherman Juha Feodoro (left) and Finnish fisherman Lauri Hämäläinen check a large fyke trap for whitefish on Lake Inari in Lapland, Finland, in 2021 (Snowchange). Page 45: (top to bottom) Feodoro (middle) and scientists sample microplastics in the Näätämö River in Lapland, Finland, in 2021 (Snowchange); Michael Kotutwa Johnson on his family's field in Oraivi Valley on the Hopi Reservation in Arizona (Michael Kotutwa Johnson); Hämäläinen (left) and Feodoro gut and clean a catch of sample whitefish as Emilia Uurasjärvi looks on (Snowchange); Otakuye Conroy-Ben at a wastewater lagoon test site (American Indian Science and Engineering Society); Michael Kotutwa Johnson with corn raised in extreme drought (Michael Kotutwa Johnson); Brad Moggridge at Bunnor Waterhole in the Gwydir Wetlands in Kamilaroi Country, Australia, in 2020 (Brad Moggridge); Ryan Emanuel prepares to walk alongside local environmental advocates in the 2018 Lumbee Homecoming parade in Pembroke, N.C. (Ryan Emanuel); Children from the Hopi Tribe learn farming practices (Maria Elena Peterson); Emanuel installs water level monitoring stations in a coastal North Carolina wetland (Ryan Emanuel); Rhianna Jones engages with participants in the Mayala Wata Restoration Project in California (John Peltier); Emanuel poses during a tour of the exhibit "Red Power on Alcatraz, Perspectives 50 Years Later" at AGU's Fall Meeting 2019 (Ryan Emanuel).

Every year, on one day in October, generations of the Washoe Tribe gather on the shores of Lake Tahoe for a day of fishing using handmade spears, harpoons, and nets made from willow, dogbane, and other traditional materials.

The Washoe have centered their lives around Lake Tahoe for thousands of years, catching and drying fish in the summers to sustain them through the winters. But in the colonialist world, the tribe of roughly 1,400 members has little access to the lake. Now, only once a year, through a partnership with the California Department of Fish and Wildlife, the Washoe hold a ceremonial day of fishing when they use traditional techniques to reduce overpopulation of nonnative kokanee salmon.

"Everybody looks forward to this day because they are not only revitalizing our traditional practices, but they are also doing something that's important for our homelands," said Washoe Tribal Council member Helen Fillmore. Fillmore is also a researcher at the University of Nevada, Reno, where she is investigating the climate resiliency of water resources on reservation lands of the Great Basin and southwestern United States, and is interning with the aquatics research team at the University of California, Davis Tahoe Environmental Research Center. One of just a handful of remaining speakers of the Washoe language, in 2017 she published a commentary on how the language can help inform hydrologic and environmental models (bit.ly/washoe-language).

"I wanted to study hydrology because I knew that it was going to be so important for my community as a whole, my family, and the ecosystems that we're a part of," Fillmore said. Fillmore's commitment to giving back to her community and working with other Indigenous communities is one shared by many Indigenous scientists and students across the world.

Like it is for Fillmore, the commitment is a dual one for Troy Brockbank of Te Rarawa, Ngāti Hine, Ngāpuhi (Māori), a stormwater engineer and a board member of Taumata Arowai, New Zealand's new drinking water regulator. Brockbank grew up next to Tāngonge, his tribe's ancestral wetland in the far north of Aotearoa (New Zealand), and developed a keen desire to protect waterways and the environment. The mission to give more than you take is ingrained in Māori culture, Brockbank said, and his work involves empowering the water industry to incorporate and normalize Māori values and perspectives for the protection of water.

"As people, we see ourselves as not only part of the environment but one and the same: Ko ahau te awa, ko te awa ko ahau—I am the river, the river is me," Brockbank said. "We've got an obligation to give back and look after what we have now; otherwise, it's lost forever."

Water Is Life

The Māori view water as a *taonga*, a gift, that has been passed down from the higher powers, and consequently, Māori people treasure and respect it, Brockbank said. Māori communities are among many Indigenous communities around the world who view water as sacred and life-sustaining and their own health as directly related to water quality.

In Finland, a land of 188,000 lakes, the traditional perspective saw lakes as sentient beings, said Tero Mustonen of the Snowchange Cooperative in Finland.

Mustonen, an adjunct professor at the University of Eastern Finland and an ethnic Karelian, is head of the small Finnish village of Selkie, and in 2016 he won an Emerging River Professional Award for his work incorporating Traditional Ecological Knowledge to monitor and restore watersheds in North Karelia, where Selkie is located. In addition to his multiple other roles—he is also a lead author of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change—Mustonen is a winter seiner, a professional fisherman who uses seine nets to catch fish under ice.

In Karelia, the lakes and rivers are traditionally seen as providers, even as mothers, and the fish catches are seen as gifts, Mustonen said. "Traditionally, you don't just go to a lake or river to use the resources—you ask for a fish," Mustonen said.

Like the Māori, the Indigenous People of the Hawaiian Islands view water as more than just a natural resource. For these people, the Kānaka Maoli, the word for water is wai. "Traditionally, many of us viewed wealth as being integrated with ecology," said Vance Kaleohano Kahahawai Farrant, a Kānaka Maoli who is studying for a master's degree in natural resources management at the University of Hawaiʻi.

For the Washoe, water is quite simply seen as life—not only does it sustain life, but also it is a life force itself. Honoring that perspective is essential to building a more sustainable relationship with freshwater resources, according to Rhiana Jones, an environmental specialist with the Washoe Tribe. Jones, a member of the Salt River Pima-Maricopa Indian Community who grew up on a Washoe reservation, is currently involved in the Mayala Wata Restoration project, which seeks to restore hydrological and ecological function to 300 acres (121 hectares) of montane meadow, which was originally a summer campsite for the Washoe people.

The meadow is currently filled with invasive conifers, which crowd out native plants that have medicinal and cultural value. The first stage of the project involves thinning densely packed lodgepole pines. The Washoe environmental team has been collecting groundwater information before the conifer removal and will continue to do so post-thinning, with the goal of quantifying how much water the invasive trees "suck up like a straw."

"Just growing up and seeing how things could be done differently from an environmental aspect, it was always important for me to come back and work for Indigenous communities," Jones said.

The short-term goal of the project is to increase the availability of water for plants that are used for medicine and food, and a long-term objective is to rehabilitate the creek that runs through the meadow, allowing for the native Lahontan cutthroat trout to spawn there once more. If all goes as planned, water will breathe life into the meadow again, Jones said.

Protecting Water Quality

The Oglala Sioux Tribe, whose home is now the Pine Ridge Indian Reservation in South Dakota, similarly sees water as life-giving and sacred, according to tribal member Otakuye Conroy-Ben, an assistant professor in the School of Sustainable Engineering and the Built Environment at Arizona State University. "So any type of pollution or activity that can impact water is very concerning," Conroy-Ben said.

"Just growing up and seeing how things could be done differently from an environmental aspect, it was always important for me to come back and work for Indigenous communities."

Given her strong connection to the land, Conroy-Ben pursued a Ph.D. in environmental engineering and went on to specialize in wastewater pollution. Her research has involved working with tribes to assess the environmental impacts of wastewater on their water supply, and she has also used wastewater to assess coronavirus prevalence in communities. "If you've been exposed to a pesticide or herbicide through your fruit consumption or if there are water contaminants, we can detect that through wastewater," Conroy-Ben said.

Conroy-Ben believes that her own perspective is bit more Western than traditional, but she stresses that learning from tribes how they've managed their natural resources is very important, especially in the light of climate change, water scarcity, and increased pollution. "I grew up with

Helen Fillmore conducts water quality monitoring in Hope Valley, Calif., in February 2020. Credit: Mo Loden, Alpine Watershed Group, 2020

Ryan Emanuel works on an atmospheric monitoring station on the campus of Appalachian State University, N.C., where he was a faculty member from 2007 until 2010. Credit: Ryan Emanuel

Ryan Emanuel installs water level monitoring stations in a coastal North Carolina wetland. Credit: Ryan Emanuel

Vance Farrant and his older brother, Nakoa Farrant, clear invasive plant species from the side of Kalou, a historic Kanaka Maoli freshwater fishpond in Waiale'e, Hawai'i. Credit: Nick Farrant

this idea you have to come back and help the community with technical expertise," Conroy-Ben said. "And now I am really excited to see how these technical fields can be merged with Traditional Knowledge."

Farming Using Minimal Water

In the United States, agriculture is a major user of groundwater and surface water, with the industry accounting for approximately 80% of the nation's water use. But the Native American Hopi Tribe in northern Arizona has learned how to grow a diverse array of crops without irrigation and with less than 25 centimeters of rain per year.

> "It is really our intimate relationship that we've had with our environment that has allowed us to survive."

Michael Kotutwa Johnson, a Hopi tribal member, learned how to farm from his grandfather. He studied conventional agriculture and earned a Ph.D. in natural resource management at the University of Arizona. He now lives back on the Hopi Reservation, farming, working on his traditional stone home, and conducting Indigenous agriculture conservation–related research. His mission is to promote the sustainability and viability of Native American agriculture and, as a 128th-generation Hopi farmer, to bring more Hopi back to farming.

"To be a Hopi farmer, you have to almost be what they call an agronomist, a hydrologist, and an engineer," Johnson said. All the techniques that the Hopi use are designed to conserve soil moisture, and over time, tribal farmers have developed drought-tolerant varieties of lima beans, tepary beans, and string beans, and more than 21 varieties of corn. "We raised corn to fit the environment and didn't manipulate the environment to fit the corn," Johnson said. "It is really our intimate relationship that we've had with our environment that has allowed us to survive."

Johnson sees his value as bringing recognition to Indigenous techniques and conservation agriculture, and in July 2021 he published a paper in the *Journal of Soil and Water Conservation* on how to enhance the integration of Indigenous Knowledge about agriculture into natural resource conservation (bit.ly/indigenous-ag).

Johnson feels blessed to have an education, and he credits his Ph.D. with getting him a place at the table where policy decisions are made. He feels even more blessed to have grown up learning traditional farming techniques. "Indigenous agriculture uses the environment to its full potential, and it gives us all these gifts back," Johnson said. "My position is to show that we can still practice this way."

Bridging the Divide

Giving voice to Indigenous Knowledge is also a focus of Bradley Moggridge, a hydrogeologist and associate professor in Indigenous water science at the University of Canberra in Australia. Moggridge, a Murri from the Kamilaroi Nation 800 kilometers northwest of Sydney, is working directly with Indigenous Knowledge holders, and his long-term mission is to promote Aboriginal Traditional Ecological Knowledge to the point that it can inform water management policy decisions in Australia.

"As I progressed, career-wise, I could see that there was a huge gap where science and Knowledge were not connecting with each other," Moggridge said. Aboriginal Knowledge is perceived as inferior to Euro/Western science, and yet there are thousands of generations of wisdom and experience encoded in Traditional Ecological

Knowledge, he explained. In particular, this Knowledge might provide vital insights into building resilience in the face of climate change. "Aboriginal people have adapted and mitigated and evolved to the driest inhabited continent on Earth, and without that evolution, they would have died out thousands of years ago," Moggridge said.

One approach Moggridge has taken to bridge the divide between Western science and Indigenous Knowledge has been to try to influence the academies to change. Moggridge is on the editorial team for the *Australasian Journal of Water Resources,* and in June 2021 the journal ran a special issue for which Moggridge prepared an editorial and a paper: "Indigenous Water Knowledge and Values in an Australasian Context" (bit.ly/indigenous-editorial). The special issue had the goal of raising the profile of Indigenous water science and highlighting successes in water research by or with Indigenous Peoples.

Indigenous authors led or coauthored all of the papers for the special issue, and the lead author of one paper was not a scientist but the Martuwarra Fitzroy River. Coauthor Anne Poelina, a Nyikina woman who is Yimardoowarra (of the river), proposed the river for lead authorship in recognition of its relational being and its role as "the holder of knowledge."

The paper illustrates that many Indigenous communities view knowledge not as something owned by individuals but as a resource for everyone concerned. Given the value of Indigenous Knowledge, one of Moggridge's missions is to encourage Western scientists to recognize, accept, and consider such knowledge. "Hopefully, special editions like this one will make a difference," Moggridge said.

Creating Community

Being an Indigenous scientist can be lonely in Australia, as it is a big continent, Moggridge said. Consequently, another of his missions is to create an Indigenous science network. "so we can talk, share, mentor, value each other's endeavors, and celebrate our domains," Moggridge said.

Building a community was one of the key goals of an Indigenous symposium on water research, education, and engagement held in the United States in August 2018. The symposium brought together 36 Indigenous scientists, community activists, elders, and allies to discuss strategies for improving Indigenous participation in hydrology and how to address water-related challenges in Indigenous communities. "We thought it was a good idea to convene as a group, to share our ideas, to support up and coming hydrologists, and to really get a grasp on the state of the future as it affects tribal nations," said Conroy-Ben, a colead of the project, which was led by Karletta Chief of the University of Arizona.

Since the symposium, which was supported by the National Science Foundation, Conroy-Ben believes there has been more collaboration and support between researchers. "Without these spaces, and without the funding, we don't have the luxury to ever sit down together in a venue and talk in a focused and deliberate way about these issues," said Ryan Emanuel, an ecohydrologist at North Carolina State University who was one of the four Indigenous coleads of the symposium.

Emanuel, an enrolled member of the Lumbee Tribe of North Carolina, said that in recent years, professional societies in the United States have been very supportive in giving Indigenous scientists sandboxes or incubation areas to discuss water issues. "These are places where we feel comfortable exploring what it means to walk in two worlds," Emanuel said.

Rhianna Jones engages with the Mayala Wata Restoration Project in California. Credit: John Peltier

Vance Farrant stands in front of Kalou, a historic Kanaka Maoli freshwater fishpond in Waiale'e, Hawai'i. Credit: Nick Farrant

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

Ryan Emanuel visits a wetland in Robeson County, North Carolina. Credit: Ryan Emanuel

From Science to Policy

Growing up, Emanuel spent a lot of time on traditional Lumbee territory—lush, green lands of forests and row crops, full of swamps and wetlands, which run alongside the Lumbee River. It took time for him to settle on a career as a hydrologist, and it was unclear how doing so would help him give back to his community.

"In my community, you were urged to get an education, so that you can help your people," Emanuel said. "But I didn't know what it would look like for a scientist to bend that expertise back to the community." Emanuel originally focused on being a good hydrologist, role model, and mentor for Indigenous students, but in the past few years, he found his way to "bend back" by using his science skills to collaborate with Native American tribes and solve problems related to justice and equity.

"If you're an Indigenous scholar working with your community, you may be a hydrologist, but sometimes you may be called on to write a policy paper."

Using geospatial analysis, Emanuel was able to demonstrate that the proposed Atlantic Coast Pipeline would disproportionately affect Native Americans in North Carolina, despite claims to the contrary. Eventually, plans for the pipeline were canceled, but Emanuel's environmental justice work had just started.

Emanuel was the lead author of a paper published in June 2021, that demonstrated that the 320,000 miles (514,990 kilometers) of major natural gas pipelines crisscrossing the country are disproportionately concentrated in vulnerable counties, those considered more likely to be affected by hazards and disasters (bit.ly/pipeline-vulnerable).

Previously, regional case studies had shown that the oil and gas industries had disproportionate impacts on socially vulnerable populations who live where the resources are extracted and where they are refined or consumed. "Individual studies seemed to point to this infrastructure regularly affecting poor or minoritized populations," Emanual said. "We wanted to see if this was a national trend." It was, they found.

The scientific quantification of such environmental injustices has to move beyond publishing pure science and into the realm of policy, supporters say. In 2020, Emanuel coauthored a paper on how to address the barriers to Indigenous participation in water governance (bit.ly/breaching-barriers). "If you're an Indigenous scholar working with your community, you may be a hydrologist, but sometimes you may be called on to write a policy paper," Emanuel said. "And if nobody else is going to do it, sometimes you have to do it."

Playing the Long Game

Being an Indigenous scientist who works with Indigenous communities is more than a full-time job, according to Emanuel and Moggridge. Emanuel admitted that the added dimension of balancing obligations to his community with those to his institute can be tricky because the expectations of each don't align perfectly.

"People in my community are suffering from pollution and from the impacts of climate change, and that weighs on me—I have a commitment to respond to those needs," Emanuel said. "But because I'm one person and not a clone, that means I have to figure out how to judiciously divide my limited time between these different things I love doing."

For Moggridge, it is important to protect Indigenous researchers from "cultural loading," whereby every Indigenous inquiry, request, project, or complaint automatically gets forwarded to the only Indigenous staff member in an organization. "But our other challenge is saying no," Moggridge said. "If we say no, it is left to non-Indigenous people to tell our science story." (Emanuel, too, prefers the term "cultural loading" over "added labor" or "cultural taxation." He stresses that he chooses, and is honored, to serve through his various commitments but also recognizes that sometimes the toll on his time and energy can feel unsustainable.)

The answer to more effective time management may lie in encouraging more Indigenous students to enter careers in the Earth sciences, Emanuel said. "That is the long game—building capacity in the next generation of scholars."

Emanuel, like many Indigenous academics, acts as an adviser and mentor for Indigenous students who might want to pursue a career in the geosciences. When Jocelyn Painter, a member of the Winnebago Tribe of Nebraska, first met Emanuel, she was an undergraduate engineering student. Inspired by the type of work he does, she is now a graduate student in his group at North Carolina State University.

As part of her graduate work, Painter works with tribal communities to gain an understanding of their connection to nearby water resources and the concerns they have about climate change. She also searches through tribal-led climate adaptation plans and the science literature and has compiled her collected data into reports that will be given to the state government, with the goal of bringing the voices of Native American tribes to the policymaking table in North Carolina. "Long term, my dream would be working with tribal communities and doing the research that they are interested in me doing—the research that is important to them," Painter said.

Other students have found their own paths to working with their communities. Farrant wrote his senior thesis for his Earth science degree at Stanford University on his work on wetland taro patches with a Native Hawaiian organization, Hoʻokuaʻāina. He is also involved in the restoration of a wetland in WaiaIeʻe, a place on Oʻahu near where he grew up. Farrant's interests in Traditional Ecological Knowledge were sparked in high school, where Indigenous students and teachers discussed culturally informed ecological practices and principles. "The cultural aspect is pretty key in my interest in the Earth sciences and helps influence how I think about my connection to the land and ocean," Farrant said.

Emanuel is encouraged that more Indigenous students are entering the Earth sciences and integrating collaborations with communities at an earlier stage in their careers. He hopes that his is the last generation of Indigenous scientists who have gone through the Western science education process only to have to figure out how to give back to their communities on their own.

Moggridge concurs. Traditionally, Indigenous People in Australia have trained in education, law, or health care so that they can contribute to their communities, he said. "I want to show Indigenous People that they can enjoy, and do, science". "And if you have an interest in caring for your country and having a say in how it's managed, you can do that by taking this career pathway."

Evenki Indigenous fishermen seine fish the River Lena in the Republic of Sahha-Yakutia, Russia. Credit: Snowchange, 2016

Ishmi Enos fishes at Taylor Creek in South Lake Tahoe, Calif., in October 2015. Credit: Helen Fillmore

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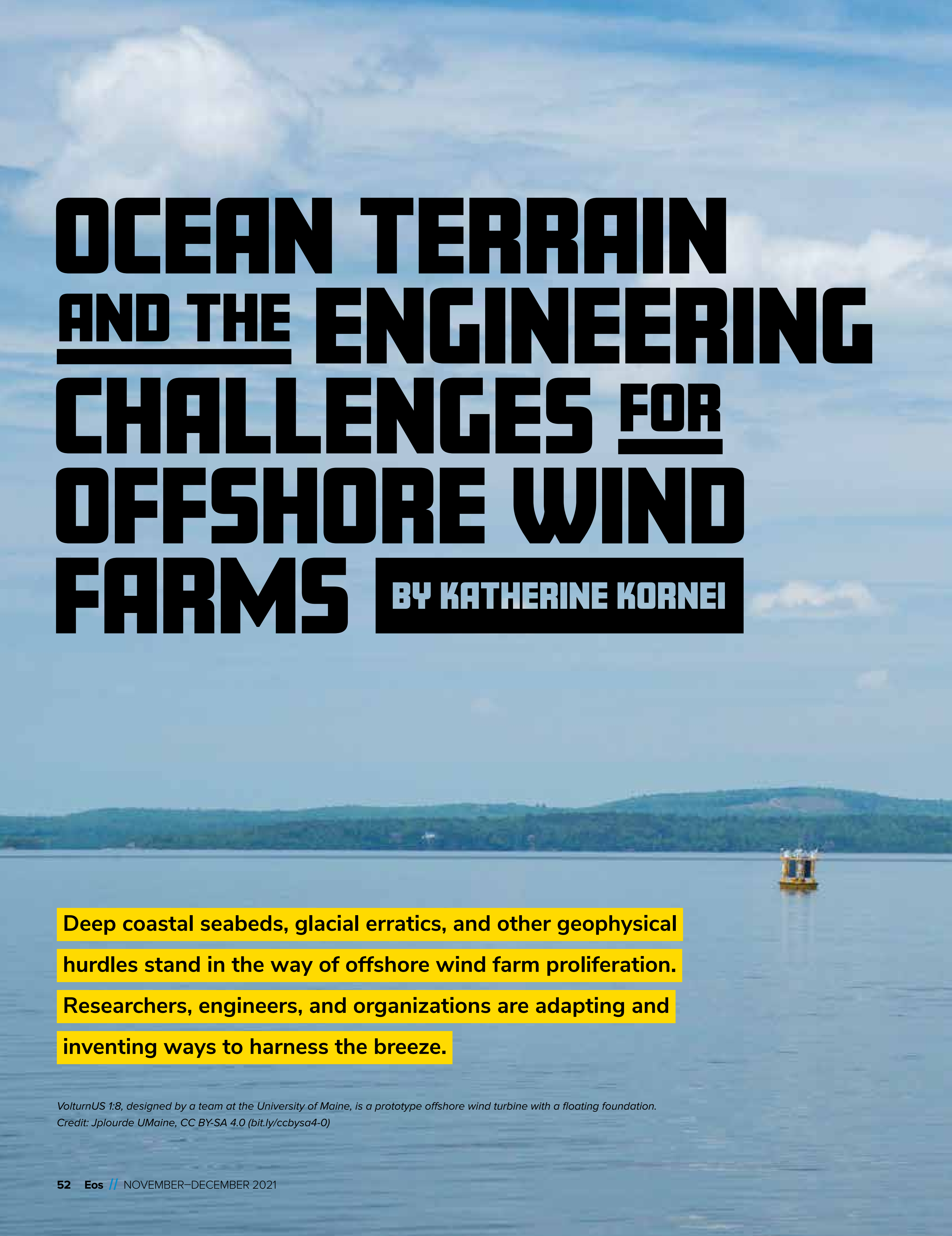
▶Read the article at bit.ly/Eos-Indigenous-water

OCEAN TERRAIN AND THE ENGINEERING CHALLENGES FOR OFFSHORE WIND FARMS

BY KATHERINE KORNEI



Deep coastal seabeds, glacial erratics, and other geophysical hurdles stand in the way of offshore wind farm proliferation. Researchers, engineers, and organizations are adapting and inventing ways to harness the breeze.

VolturnUS 1:8, designed by a team at the University of Maine, is a prototype offshore wind turbine with a floating foundation. Credit: Jplourde UMaine, CC BY-SA 4.0 (bit.ly/ccbysa4-0)


VOLTURNUS 1:8

Europe has long embraced offshore wind farms—the first one was built off the coast of Denmark in 1991. More than 5,400 grid-connected turbines in European waters generate around 25 gigawatts, which is more than 70% of the offshore wind power produced globally today.

Offshore wind farms are now gaining traction in the United States, which is currently home to just seven offshore wind turbines and produces 42 megawatts—less than 0.1% of the world's offshore wind energy. Several commercial-scale facilities are in development in U.S. waters, and earlier this year, the Biden administration set forth the goal of producing 30 gigawatts of offshore wind power by 2030.

That's an audacious target, but it's also an important one: Wind is free and often plentiful, and the energy it supplies can reduce reliance on fossil fuels, which are currently used to produce nearly 60% of the electricity generated in the United States.

THE BIDEN ADMINISTRATION SET FORTH THE GOAL OF PRODUCING 30 GIGAWATTS OF OFFSHORE WIND POWER BY 2030.

A more sustainable future is clearly in sight as offshore wind farms proliferate globally and increase in capacity. But building and operating offshore wind farms come with their own set of challenges, ranging from accurately surveying the seafloor to constructing floating foundations in deep water. These challenges are testing the mettle of scientists and engineers alike, but with the latest report from the Intergovernmental Panel on Climate Change warning that warming will reach 1.5°C by the early 2030s, there's strong impetus to succeed.

The Many Benefits of Going Offshore

Right now more than 99% of wind farms in the United States are land based. Wind farms on land have significant limitations, the primary one being that 40% of U.S. residents live in coastal counties where space is at a premium.

"You have major population centers on the East Coast that are looking to benefit from the development of renewable energy," said Darryl François, chief of the engineering and technical review branch for the offshore energy program at the Bureau of Ocean Energy Management (BOEM). "For large, commercial-scale, utility-type projects, you need a lot of open acreage"—that's tough to find near these metropolitan areas.

Moving wind farms offshore presents a viable solution. Producing power near major population centers suddenly becomes feasible, and doing so minimizes transmission-related losses, said François. "You can deliver [energy] where it's needed."

Offshore wind farms also reap the benefits of the stronger, more predictable winds commonly found at sea. "There's almost always much more wind and consistent wind offshore," said Dan Lizarralde, a geophysicist at Woods Hole Oceanographic Institution (WHOI) in Massachusetts. That's true in part because there's nothing—no mountains or trees—to block the wind, he said.

And where these wind farms are going, they don't need roads—that's good because modern wind turbines can be hundreds of meters in diameter. "Offshore wind turbine components are transported by ships and barges," said Jocelyn Brown-Saracino, offshore wind lead at the U.S. Department of Energy, "reducing some of the logistical challenges that land-based wind components encounter, such as narrow roadways or tunnels."

Moving offshore can also sidestep a myriad of state, local, and other jurisdictional regulations and permitting requirements, said François. "You're working with one landlord, which is the federal government." (Wind farms lease parts of the Outer Continental Shelf, a vast region generally defined as beginning 3 nautical miles offshore and extending to 200 nautical miles, from BOEM, an agency of the U.S. Department of the Interior.)

All of the sites leased for offshore wind farms in the United States have thus far been located on the Atlantic coast. (Two, the Coastal Virginia Offshore Wind project and Rhode Island's Block Island, have been developed with wind farms and have a combined capacity of 42 megawatts—sufficient to power roughly 20,000 homes.) Leasing the Atlantic continental shelf is not surprising given the bathymetry of the area, said Anthony Kirincich, an oceanographer at WHOI. "We have a very shallow, wide shelf."

Ways to Avoid Hitting Rock Bottom

The shallow waters of the Atlantic coast (often fewer than 30 meters in depth) make it relatively straightforward to install the foundations that support a wind farm's turbines. Furthermore, the wide continental shelf allows for more turbines to be installed farther offshore, which homeowners appreciate. "They're out of sight, out of mind," said Kirincich.

More than a lack of aesthetic appeal, there are geophysical reasons wind farms don't line the shore. Boulders the size of houses and submarine trenches as deep as the Grand Canyon make installing turbines more than just challenging; it is often impossible.

Massive boulders known as glacial erratics dot much of the New England coastline.

Offshore wind farms, like this one off Block Island, R.I., are promising sources of energy, but installing one requires a lot of engineering and scientific investigation. Credit: Dennis Schroeder/National Renewable Energy Lab, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

BOULDERS THE SIZE OF HOUSES AND SUBMARINE TRENCHES AS DEEP AS THE GRAND CANYON MAKE INSTALLING TURBINES MORE THAN JUST CHALLENGING; IT IS OFTEN IMPOSSIBLE.

They're relics of the last period of glaciation, which ended roughly 20,000 years ago. These erratics can sit on the seafloor or be buried under the surface. Their presence can significantly set back a project, said Lizarralde, particularly if one is discovered during the process of anchoring a turbine by sinking enormous steel pipes 30 meters into the seafloor.

Sonar can reveal exposed boulders on the seafloor, but buried features are tougher to spot. To pinpoint underground glacial erratics, researchers often turn to seismic reflection surveying. This technique involves passing sound waves through the seafloor and recording how they're transmitted and reflected. These measurements allow geoscientists to infer the presence of geological features, including boulders. Even so, scientists' ability to really see what's down there remains limited, said Lizarralde. "We have poor knowledge of what's below the seafloor."

Developers sometimes look for ways to avoid digging into the seafloor. Ørsted, an energy company with headquarters in Denmark, recently opted not to bury the transmission cables of several of its offshore wind farms, eschewing standard practice. To protect the seafloor from the heavy cables, they deliberately placed rocks beneath the lines in an effort to prevent erosion. That practice turned out to be a mistake—the rocks ended up abrading the cables, some to the point of failure.

Besides keeping an eye out for rocks, developers must also survey the properties of the seafloor itself, such as its slope and composition, said Sanjay Arwade, a professor of civil engineering and associate director of the Wind Energy Center at the University of Massachusetts Amherst. Most offshore wind turbines are rigidly connected to the seafloor via a foundation, the design of which is informed by local conditions. Common designs include a so-called monopile (a single long, hollow pipe sunk into the seafloor), a jacket foundation (a three- or four-legged structure affixed to the seafloor), and a gravity base (a large mass, typically a block of concrete, resting on the seafloor).

Careful surveying is therefore necessary to evaluate a potential site, said Arwade. A "site investigation [to discover what the geology and geotechnical properties are] allows the design engineers to do their job."

The marine environment also brings with it many other fundamental challenges. Installing and maintaining wind turbines at sea necessitate a ship, specialized equipment, and professional divers. Waves impart stress on turbine foundations, and storms—such as nor'easters and hurricanes—can kick up larger-than-normal waves that batter structures. And at some point off the coast the economic benefit of building a wind farm plummets to zero: "As the water depth gets beyond 50 meters or so, building a fixed-bottom support structure becomes borderline uneconomical or completely uneconomical."

Floating in Deep Water

Water depth is one of the primary reasons offshore wind farms don't yet dot the West Coast: The continental shelf there tends to fall off much more steeply, and water depths routinely exceed 30 meters close to shore. Researchers and engineers at the University of Maine decided to take on this challenge by developing a new type of wind turbine with a floating foundation intended to be deployed in deeper waters.

“We formed the very first university-based research team on floating wind technologies,” said team leader Habib Dagher, executive director of the University of Maine’s Advanced Structures and Composites Center. Maine is home to some of the speediest offshore winds in the United States, but its coastal waters are as deep as those on the West Coast.

The project, launched in 2007, aims to satisfy immediate needs—an alternative to the rising costs of heating oil in the state—as well as alleviate long-term concerns about fossil fuel use and climate change, said Dagher. “Our concerns about global climate change are very real.”

Over 6 years, the team designed and built a one eighth scale model of a single-turbine facility capable of producing 6 megawatts of electricity. The three-pronged floating concrete hull had a draft of 3 meters and was anchored to the seafloor with three mooring lines.

VolturnUS 1:8 performed extremely well during its 18-month deployment: Even during stormy conditions, it never heeled by more than 6°.

In June 2013, the team towed its prototype, called VolturnUS 1:8, just off the coast of Castine, Maine. The following month, the facility began delivering electricity to the Central Maine Power Company grid via an undersea cable. The researchers generated energy, along with a slew of data. More than 50 sensors recorded environmental conditions and the structure’s response to those conditions, including accelerations, strains, and loads on the mooring lines. The data revealed that VolturnUS 1:8 performed extremely well during its 18-month deployment: Even during stormy conditions, it never heeled by more than 6°.

“It was a very successful program,” said Dagher.

In addition to opening new regions of continental shelves to offshore facilities, floating platforms also sidestep a common problem associated with rigid foundations: the noise produced by driving support structures deep into the seafloor. “Everyone wants to be aware of and careful of the potential impacts of construction noise on marine life.”

Given the potential of floating platforms, Dagher and his collaborators are currently designing a full-scale model of an 11-megawatt floating facility that builds on the lessons learned from VolturnUS 1:8. Known as the New England Aqua Ventus I project, it’s slated to be in operation by 2024 and to produce power off the coast of Maine for more than 20 years.

Transporing wind turbine blades can pose many challenges, as seen during this delivery of blades to Muirhall Windfarm in South Lanarkshire, U.K. Credit: ShellAsp, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Looking Ahead: The Knowns and Unknowns

Offshore wind farms, both affixed to the seafloor and floating, will no doubt proliferate in U.S. waters. Just a few months ago, BOEM approved the development of an offshore wind farm south of Martha’s Vineyard, Mass. It’s slated to include 62 wind turbines, each topping 250 meters in height and each capable of generating 13 megawatts. The developer, Vineyard Wind, estimated that the power this facility will produce—roughly 800 megawatts—will be sufficient to supply more than 400,000 homes on the Eastern Seaboard.

The Martha’s Vineyard project is an important contributor to the growth of the offshore wind energy sector, but there’s a lot more in the pipeline, said François. If all of the projects under lease right now along the Atlantic coast are developed, he said, the potential capacity of offshore wind energy in the United States is 19–21 gigawatts.

Over on the Pacific coast, California governor Gavin Newsom announced in May an agreement to open up parts of the West Coast for offshore wind farms, with most using floating foundations. BOEM plans to offer leases off the central and northern coasts of the Golden State as early as next year.

As with any new infrastructure, sometimes only time will tell engineers what they need to know. Kirincich noted that there’s a lack of understanding of how wind turbine structures corrode over time and how their blades fatigue with age. “Most of these structures are designed for hurricane-force winds,” he said, but “how good is the corrosion coating?”

Nevertheless, in the very near future, Los Angeles beachgoers will likely be able to squint between the surfers to see flocks of swiftly turning turbine blades crowding out the offshore oil rigs. Geoscientists and engineers must work together to overcome the issues presented by ocean terrain and new technologies meant to last a lifetime. Progress often comes in leaps and bounds. In this case, it comes in gales.

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Hear Ye! Hear Ye!

A Declaration of the Rights of the Moon

BY KATE EVANS

What are the ethics of mining the Moon? Could humans cause environmental damage to Earth's only satellite? And could a new Declaration of the Rights of the Moon be one way of mitigating those impacts?

James Shook/Wikimedia, CC BY 2.5 (bit.ly/ccby2-5)

Sometime this decade, humans will probably stand on the Moon for the first time since 1972. U.S. president Joe Biden recently committed to NASA's Artemis program, which aims to land the first woman and the first person of color on the lunar surface by 2024. Other countries and private companies want to send people, too.

This time, they might take more than photographs and a few rocks.

Mining on the Moon is becoming increasingly likely, as growing numbers of countries and corporations hope to exploit its minerals and molecules to enable further exploration and commercial gain. The discovery of water on the lunar surface has raised the possibility of permanent human settlement, as well as making the Moon a potential pit stop on the way to Mars: Water can be split into hydrogen and oxygen and used to make rocket fuel.

In 2015, the U.S. Congress and President Barack Obama passed legislation that unilaterally gave American companies the right to own and sell natural resources they mine from celestial bodies, including the Moon. In 2020, President Donald Trump issued an executive order proclaiming that "Americans should have the right to engage in commercial exploration, recovery, and use of resources in outer space...and the United States does not view it as a global commons."

Other countries are also interested in exploring our nearest celestial neighbor. In 2019, China landed a probe on the farside of the Moon. Russia is resurrecting its Moon program, planning a series of missions starting in 2022 to drill into the surface of the lunar south pole and prospect for water ice, helium-3, carbon, nitrogen, and precious metals.

Corporations have been plotting out their own ways to claim resources on the Moon, including U.S.-based SpaceX and Blue Origin, and the Japanese lunar exploration company ispace—which, according to its website, aims to mine water and "spearhead a space-based economy." The company also anticipates that by 2040 "the Moon will support a [permanent] population of 1,000 people with 10,000 visiting every year."

But what effects might these activities have on Earth's only natural satellite? Who gets to decide what happens on the Moon?

We, the People of Earth

In a bid to get more people thinking about these questions, and to start a conversation about the ethics of exploiting the lunar landscape for profit, a group of mainly Australian academics have come up with a draft Declaration of the Rights of the Moon, which they hope members of the global public will sign and discuss.

"We the people of Earth," the declaration begins, before going on to assert that the Moon is "a sovereign natural entity in its own right and...possesses fundamental rights, which arise from its existence in the universe." These rights include "the right to exist, persist and continue its vital cycles unaltered, unharmed and unpolluted by human beings; the right to maintain ecological integrity...and the right to remain a forever peaceful celestial entity, unmarred by human conflict or warfare."

Given the acceleration of planned missions and ongoing legal uncertainty over what private companies are allowed to do in space, the authors said, "it is timely to question the instrumental approach which subordinates this ancient celestial body to human interests." Now is the time, they said, to have a clear-eyed global debate about the consequences of human activity in a landscape that has remained largely unchanged for billions of years.

The declaration was penned after a series of public fora organized by Thomas Gooch, a Melbourne-based landscape architect. The discipline of landscape architecture is well suited to having a voice in Moon exploration, he said: "We walk the line of science, art, creativity, nature, and human habitation."

Existing international space agreements address safety, conflict reduction, heritage preservation, sharing knowledge, and offering assistance in emergencies. These are all people-centric concerns; the aim of the declaration is to give the Moon a voice of its own, as a celestial body with an ancient existence separate from human perceptions, Gooch said.

The Moon might not have inhabitants or biological ecosystems—or, at least, we haven't found any yet—but that doesn't mean it is a "dead rock," as it is sometimes described. "Once you see something as dead, then it limits the way you engage with it," said Gooch.

THE AIM OF THE DECLARATION IS TO GIVE THE MOON A VOICE OF ITS OWN, AS A CELESTIAL BODY WITH AN ANCIENT EXISTENCE SEPARATE FROM HUMAN PERCEPTIONS.

The declaration, as coauthor Alice Gorman sees it, is a position statement to which companies and countries operating on the Moon could be held accountable. Gorman is a space archaeologist studying the heritage of space exploration (and the junk humans leave behind) at Flinders University in Adelaide, Australia.

"Have they respected the Moon's own processes?" she asked. "Have they respected the Moon's environment? Some of the time, the answer to that is going to be no, because you can't dig up huge chunks of a landscape and expect there to be no impact.

"But if that's the guiding principle, if that's something that they're attempting to achieve from the beginning, then that's surely got to give us a better outcome than if we turn around in 10 years' time and realize that if you look at the Moon with the naked eye you can see the scars of mining activities."

The Dusty, Living Moon

Recent discoveries suggest the Moon is a much more complex and dynamic place than was previously thought, said Gorman.

It has seismic activity, including moonquakes and fault lines. Ancient water ice was directly observed at both lunar poles in 2018, hiding in shadowy areas that haven't seen sunlight in 2 billion years. "Surely that's environmentally significant," said Gorman. "Even in completely human terms, 2-billion-year-old shadows are aesthetically significant."

Individual water molecules have also recently been identified on the Moon's sunlit surface, and there may even be a water cycle happening, with the molecules bouncing around over the course of a lunar day.

Gorman is vice chair of an expert group affiliated with the Moon Village Association, an international organization that hopes to establish a permanent human presence on the Moon. "I'm as motivated by the excitement of space science as the most hardcore space nut," she said.

As such, she recognizes it's inevitable that human activities—building a village, conducting scientific experiments, or extracting minerals—will have some kind of environmental impact on the Moon. Mining will require extraction machinery, processing facilities, transportation infrastructure, storage, and power sources, Gorman said. "It's not just, 'Let's dig a hole on the Moon.'"

Lunar dust, for instance, is an important concern. Sticky, abrasive, and full of sharp fragments of obsidian, it eroded the seals on Apollo astronauts' spacesuits and coated their instruments, making data hard to read. It smelled of "spent gunpowder," gave Apollo 17's Harrison Schmitt a kind of hay fever, and turned out to be extremely hazardous to respiratory health—the grains are so sharp they can slice holes in astronauts' lungs and cause damage to their DNA.

Machinery designed to operate on the Moon will need to be resistant to abrasion by the lunar dust. And some research suggests that too many rockets landing on and taking off from the Moon could lift significant quantities of dust into the exosphere. "There's the potential to create a little dust cloud around the Moon," said Gorman, "and we don't yet know enough about how the Moon operates in order to properly assess those impacts."

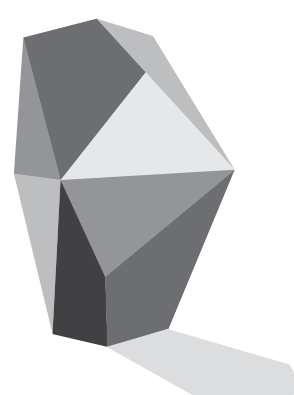
A Space for Capitalism

In theory, existing space law should already protect the Moon from commercial exploitation, said Gbenga Oduntan, a reader in international commercial law at the University of Kent in the United Kingdom. Originally from Nigeria, Oduntan was inspired to study law by the fact that nations got together to agree on and create the Outer Space Treaty—a "beautiful" idea that made him "proud of mankind."

In the treaty, which came into effect in 1967, nations agreed that space (including the Moon) "is not subject to national appropriation by claim of sovereignty" and that "exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind." For Oduntan, the meaning is clear: Mining on the Moon would be legal if the resources were used for further exploration and scientific research on behalf of all humanity, "but appropriation for sale is a vastly new territory which we cannot allow countries, not to mention companies, to run along with on their own," he said.

Successive U.S. administrations have had a different interpretation: that outer space is a space for capitalism. In 1979, the United States refused to sign the Moon Agreement, another United Nations treaty that specifically declared that lunar resources were the "common heritage of mankind" and committed signatories to establishing an international regime of

MINING WILL REQUIRE EXTRACTION MACHINERY, PROCESSING FACILITIES, TRANSPORTATION INFRASTRUCTURE, STORAGE, AND POWER SOURCES. "IT'S NOT JUST, 'LET'S DIG A HOLE ON THE MOON.'"



New Zealand's Whanganui River is one of a growing number of natural entities that have been granted legal rights. Credit: James Shook/Wikimedia, CC BY 2.5 (bit.ly/ccby2-5)

"JUST BECAUSE AN AREA IS BEYOND SOVEREIGNTY DOESN'T MAKE IT A GLOBAL COMMONS."

oversight when resource extraction was "about to become feasible." (Lack of support from the major space powers led to only 18 countries signing it, and it remains one of the most unpopular multilateral treaties.)

Instead, in 2015, once extraction actually *was* about to become feasible, the Space Act explicitly gave U.S. companies the right to own and sell resources they mine from space, as well as 8 more years mostly free of government oversight. (In a 2015 article, Oduntan called it "the most significant salvo that has been fired in the ideological battle over ownership of the cosmos.")

Scott Pace, a professor of international affairs at George Washington University and director of the U.S. Space Policy Institute, said that legally speaking, space is not a global commons. (In his former role as head of the National Space Council, Pace worked on the 2020 Trump executive order—which also explicitly repudiated the Moon Agreement.)

"Just because an area is beyond sovereignty doesn't make it a global commons," he said. "Commons implies common ownership and common responsibility, which means…[other countries get] a say in what the United States does out there."

Instead, the official American view is that "rules on frontiers and shared domains are made by those who show up, not by those who stay behind," as Pace put it. To that end, the United States has signed nonbinding bilateral agreements—the Artemis Accords—with, so far, 11 other countries that hope to work with the United States on upcoming lunar missions. The accords aim to set norms of behavior for activity on the Moon, Pace said, although some experts have pointed out that they might also be designed to reinforce the U.S. interpretation of the Outer Space Treaty on resource exploitation.

Oduntan believes that all countries *should* get a say in what happens in space and on the Moon, even countries that are not yet capable of or interested in going there. Such a perspective is not about "exporting communism into outer space," he said. Instead, the point is to recognize that conflict over resources is inevitable. "Commercialization of outer space in a Wild West mode is going to lead faster to disputes. There will be turf wars. And experience shows us that lack of regulation leads to tears."

Rock Rights

So could giving the Moon its own rights be one way to provide that kind of oversight and help ensure that countries and companies act in ways that minimize harm to its environment?

The Declaration of the Rights of the Moon was inspired by the growing Rights for Nature movement and uses some of its language. In the past 5 years, some natural entities—like New Zealand's Whanganui River and Urewera forest, India's Ganges River, and Colombia's Atrato River—have been granted legal rights as part of efforts to protect and restore them. (Similarly, some astronomers have been investigating legal action to stop constellations of satellites, like Space X's Starlink, from ruining their observations and altering the night sky.)

Pace was skeptical of the concept and said the Declaration of the Rights of the Moon has no legal standing.

"The idea that the Moon as an inanimate object possesses fundamental rights as a result of its existence in the universe doesn't make any sense. Rights are something which attach to human persons. We can have an argument about animal rights, but this is saying that there should be something called rock rights—that a lunar rock has a right. It's an interesting metaphor, but it doesn't have any legal foundation, and it's politically meaningless."

New Zealand's Whanganui River might now have legal rights, Pace explained, but that's because those rights were granted by the sovereign government of New Zealand. Countries agreed in the Outer Space Treaty that the Moon was beyond any nation's sovereignty. That means there is no sovereign power that could legally grant the Moon rights, Pace reasoned—and efforts to have the Moon declared a national park or a World Heritage Site have failed for the same reason. Erin O'Donnell, an expert on water law and the Rights for Nature movement at the University of Melbourne, foresees a different problem. Her research has shown that granting rights to rivers has frequently had unintended consequences for environmental protection.

Depending on the exact legal instrument used, some rivers now have the right to sue, enter into contracts, or own property. "But," she said, "none of them have rights to water."

"This is the real tension at the heart of the rights of nature advocacy movement: If something's not legally enforceable, then it may not necessarily lead to a lot of change, because you can't rely on it then in situations of conflict."

Emphasizing legal rights can set up an adversarial atmosphere that can actually make conflict more likely, she said, and even weaken community support for protecting an environment, because people assume that if something has rights, it can look after itself. "If you emphasize the legal rights to the exclusion of all else, you can end up fracturing the relationship between people and nature, and that can be very hard to recover from."

Where rights of nature movements have had success, she said, is in "reframing and resetting the human relationship with nature," often by elevating Indigenous worldviews.

Our Beloved Moon

For Pace, the declaration is premature. Norms of behavior will evolve over time, he said, once we actually get to the Moon and figure out what we can possibly achieve there.

"What you don't do is have a group of lawyers, no matter how smart, sit down in a room and try to draft up rules for things that are totally hypothetical. Environmental ethics considerations are rather speculative and not really necessary right now."

If people really want to have an influence on space policy, Pace said, they should lobby their governments to get involved in the new space race. "Make sure you're at the table. It sounds blunt, but the rules are made by the people who show up. Find a way to get in the game, and then you have a say."

Oduntan, O'Donnell, and Gorman disagreed. "By the time there's a problem, it's massively too late," said O'Donnell. "We see that in the case of the rivers every day. All of the rivers around the world that have received legal rights are beloved, but heavily impacted." The Moon is beloved, too, she said, but is as yet undamaged. "It would be nice if in this case we could act preventatively."

The Declaration of the Rights of the Moon may not result in any legal outcomes, O'Donnell said, but it's "a really important conversation starter."

Most of us will never walk on its surface, but all human cultures tell stories about the Moon. It lights our nights, is a presence in our myths and legends, powers the tides, triggers animal (and, in limited ways, human) behavior, and marks the passing of time.

"The more of us who talk about these kinds of things," said O'Donnell, "the more we're likely to normalize seeing the Moon as something other than a piece of territory to be fought over by nation states and corporate investors."

Supporters of the declaration want to democratize that conversation and give everyone a chance to take part.

"Every single person on Earth has a right to have a say in what happens to the Moon," said Gorman. "It's important for the environments in which we live, and for our cultural and scientific worldviews. It really does not belong to anyone."

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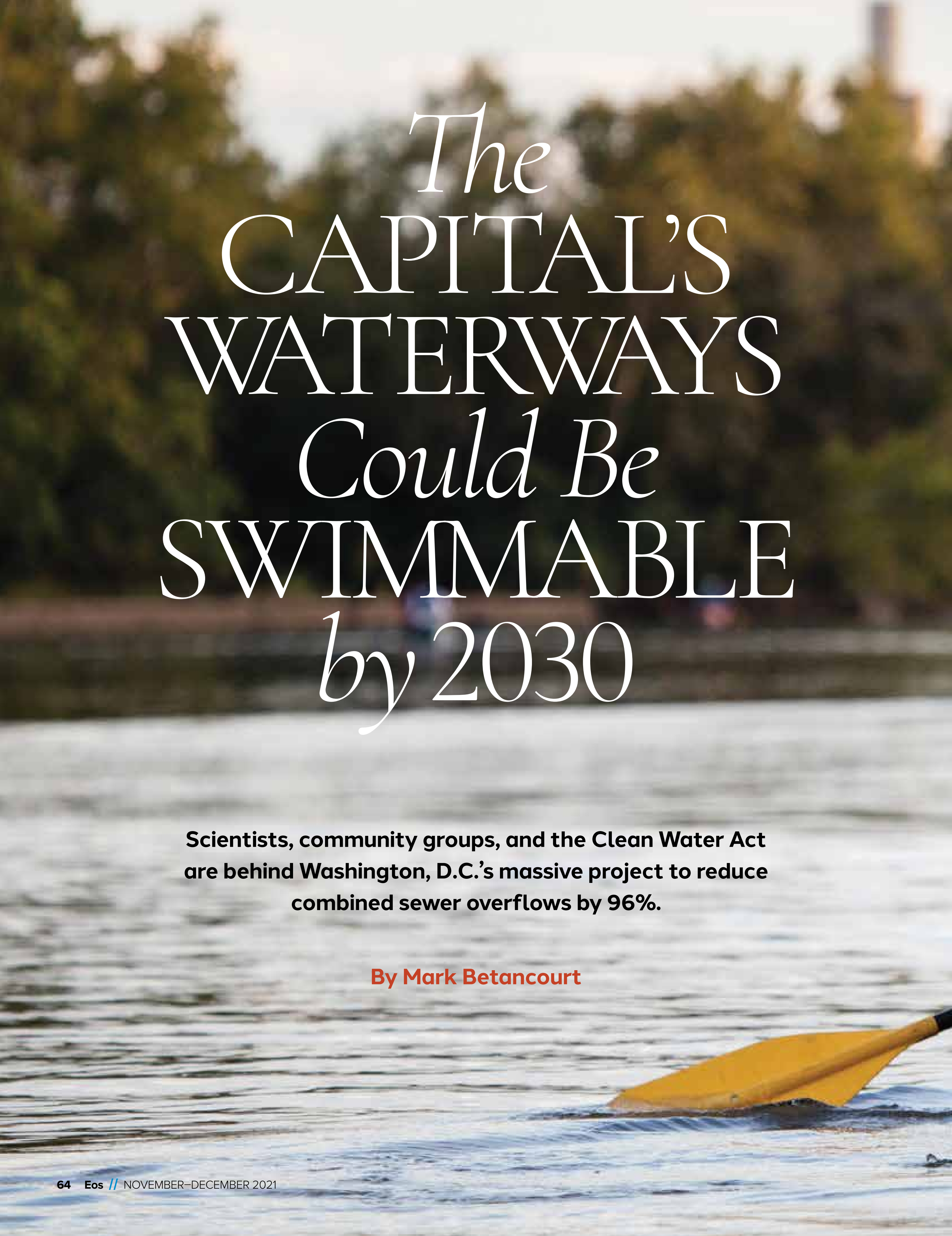
▶ Read the article at bit.ly/Eos-Moon-rights

"THIS [DECLARATION] IS SAYING THAT THERE SHOULD BE SOMETHING CALLED ROCK RIGHTS—THAT A LUNAR ROCK HAS A RIGHT. IT'S AN INTERESTING METAPHOR, BUT IT DOESN'T HAVE ANY LEGAL FOUNDATION, AND IT'S POLITICALLY MEANINGLESS."



The CAPITAL'S WATERWAYS *Could Be* SWIMMABLE *by* 2030

Scientists, community groups, and the Clean Water Act are behind Washington, D.C.'s massive project to reduce combined sewer overflows by 96%.

By Mark Betancourt

Canoers paddle along the Anacostia near Kenilworth Park in Washington, D.C.
Credit: Will Parson/Chesapeake Bay Program

In early September 2020, a freak storm dumped between 5 and 15 centimeters (2–6 inches) of rain in and around Washington, D.C., within 2 hours. My children had left a toy bucket in the yard of our home in Hyattsville, Md., just outside the city, and we watched it steadily fill to overflowing.

A few miles downstream, the sewer system of the nation's capital was doing the same thing.

Like more than 800 other communities in the United States, much of the city relies on a combined sewer system built in the late 19th century. Unlike modern sewers that transport human waste and storm water to a treatment facility in separate pipes, a combined system mixes them together. With a large and sudden enough influx of storm water, the system hemorrhages sewage.

Some of the sewage flows backward, including into people's homes. But most of it triggers a combined sewage overflow, or CSO, which means it jumps barriers and spills into the regular storm water system. From there, it has nowhere to go but downhill. In Washington, D.C., combined sewer outfalls line Rock Creek, the waterway nestled in the leafy park that winds along the capital's spine. Dozens more outfalls empty into the Potomac and Anacostia rivers, which bracket the city like a riparian wishbone.

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> *The city's goal was to avoid 80% of the sewage overflow into the Anacostia River. Now that they're operational, the tunnels are capturing 90%, along with 6,260 metric tons of trash and debris.*

The Anacostia, flanked by some of the city's least affluent neighborhoods, catches the brunt of those overflows. That day in 2020, D.C. dumped more than 680 million liters (180 million gallons) of raw sewage into the river according to the District of Columbia Water and Sewer Authority (DC Water).

It was not an isolated incident. Until a few years ago, the city saw an average of more than 180 CSOs that emptied 12.1 billion liters (3.2 billion gallons) of sewage into the rivers each year. That meant the waterways were more or less continually contaminated with high levels of fecal bacteria, traveling with their own nutrient-rich food source. Not only can a bacterial horde monopolize dissolved oxygen in a river ecosystem, killing off fish and anything else that breathes, but also it's the main form of pollution that makes urban waters unsafe for human recreation.

But thanks to local activists who came to the rivers' defense, the D.C. government is taking huge steps to curtail sewage overflows with the $2.7 billion Clean Rivers Project. Dozens of similar projects are underway in cities across the country, all with the goal of bringing their waterways into compliance with the Clean Water Act. It's an expensive undertaking, but it could make many urban waterways safe enough to swim in.

Meanwhile, D.C.'s existing sewer system is reaching the end of its life span, and the changing climate is making events like the one in 2020 more frequent. As the Clean Rivers Project nears completion, government researchers and a small army of community scientists are building an understanding of how often—and maybe for how long—the city's rivers will be swimmable.

An Old and Dirty Problem

At times, CSO events are like rancid flash floods, contaminating waters in spectacular fashion. Someone sent Dean Naujoks a video of such an overflow after a particularly intense summer thunderstorm a few years ago. Naujoks holds the position of Potomac riverkeeper with the Potomac Riverkeeper Network. "This thing shot sewage-laden storm water almost all the way across the river," he said. "I wouldn't have believed it unless I saw it."

Sewage is full of bacteria from the collective intestines of the human population. Most of them are harmless, but some pathogens can cause serious illness. Naujoks knows firsthand the danger posed by CSOs. Once, while helping a woman out of her kayak near one of the outfalls, his toe slipped into the Potomac. The toe had a cut on it, and days later his entire foot was infected.

In 1972, the Clean Water Act required that most waterways be made safe for recreation by 1983 and that no pollutants, including sewage, be discharged into any navigable waters by 1985. Nearly 50 years later, it's not clear how many waterways meet those goals. Each state is responsible for setting its own water quality standards, and states report the status of their waters to the federal government in different years. What is clear is that many urban areas, with the largest concentration of potential water users, do not yet have swimmable rivers.

Washington, D.C., has yet to comply with its own water quality standards, and its fix has been simply to ban swimming in its waterways except for permitted events, although Naujoks sees thousands of people flout the ban every summer. "There are so many undiagnosed ear and nose infections" associated with this behavior, he said. "[People] don't even think about it."

For the past decade, the city's Clean Rivers Project has been creeping toward a solution to its CSO problem a few meters of rock at a time, drilling massive "deep tunnels" (so called because they're placed underneath existing infrastructure) that are designed to temporarily store excess sewage during heavy rain events.

Birth of the Clean Rivers Project

Like so many environmental cleanup efforts, the Clean Rivers Project was the result of a lawsuit. In 2000, the Anacostia Watershed Society, along with several other organizations and a concerned citizen, sued the city over its practice of dumping combined sewage into its rivers. The U.S. EPA later joined the lawsuit as a plaintiff, citing the city's violation of the Clean Water Act.

With a grant from the EPA, the Anacostia Watershed Society had begun to monitor the river for bacteria and share the results with the public. The numbers were dire—Jim Connolly, who led the organization at the time and now sits on its board, said that the river rarely met EPA boating standards and never met swimming standards. "Those data were very helpful" in bolstering their case in the lawsuit, he said, "and the fact that it was an EPA-funded grant gave us a lot more credibility."

The city settled in 2005, signing a consent decree with the federal government that outlined an ambitious project to curtail combined sewage overflows. More than 130 other cities, including Atlanta, Baltimore, and Chicago, have signed similar agreements.

DC Water is now on the threshold of meeting the conditions of the consent decree. The first of several cavernous tunnels, each more than 30 meters (100 feet) under the city and large enough to accommodate one of its Metro trains, went into service in 2018. Carlton Ray, vice president of the Clean Rivers Project for DC Water, said the city's goal was to avoid 80% of the sewage overflow into the Anacostia with the initial phase of the project. Now that they're operational, the tunnels are capturing 90%, along with 6,260 metric tons of trash and debris to date.

"We're doing a heck of a job so far," said Ray, adding that the existing tunnels prevent CSOs only on the Anacostia. "But stay tuned. We're on track to get the rest of them."

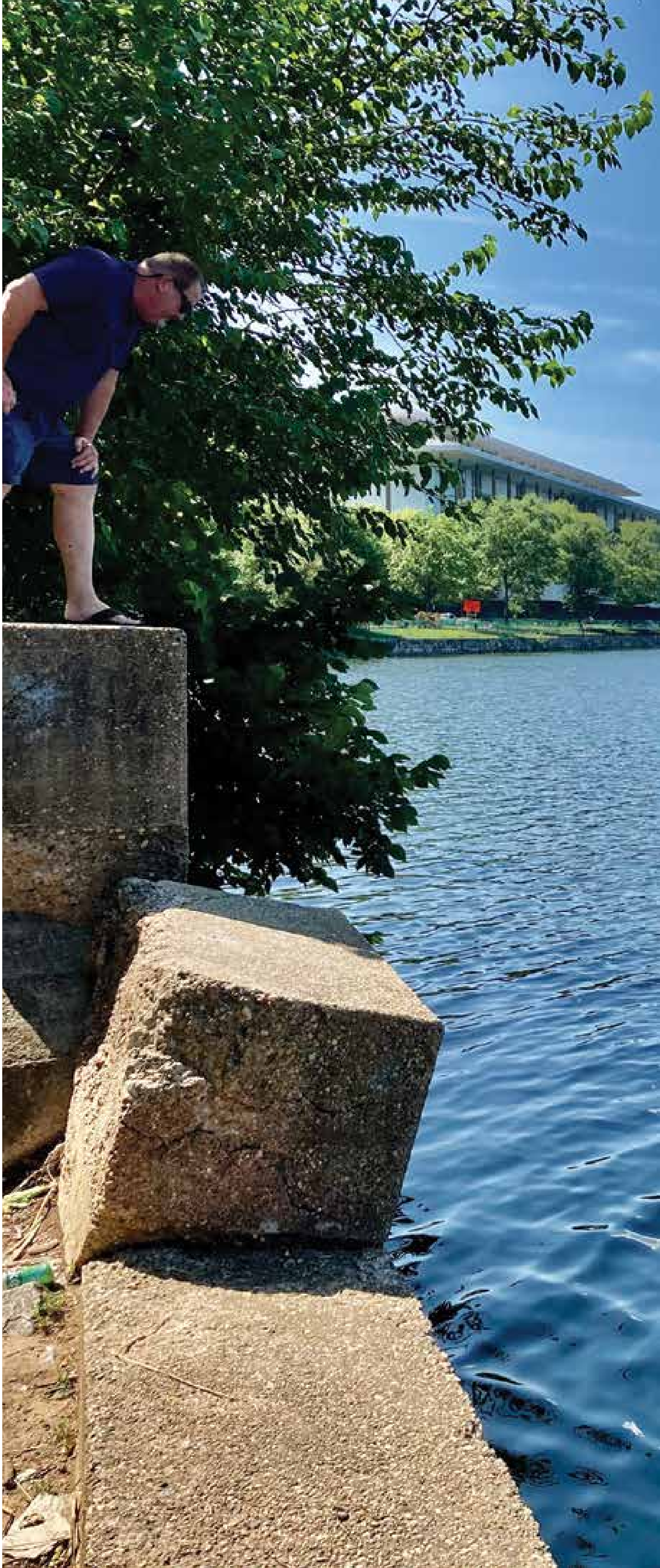
The Anacostia phase will be completed by 2023. The final section of the project, on the Potomac side, is slated to come online in 2030. By then, Ray said, 96% of the city's sewage overflow problem will be contained.

In light of that progress, many Washingtonians are hopeful the city may soon lift its decades-old swim ban. Urban planners have gone so far as to draw up plans for public swimming platforms on the Anacostia. And the monitoring data that helped force the city to act are now going straight to the people.

Crowdsourced Science Steps Up

In 2018, D.C.'s Department of Energy and Environment (DOEE) awarded a 3-year grant to the nonprofit Anacostia Riverkeeper to bulk up its monitoring program. The organization is a member of the international Waterkeeper Alliance, a network of advocacy organizations that assigns a "keeper" to each waterway. Anacostia Riverkeeper partnered with other D.C. organizations, including Naujoks's Potomac Riverkeeper Network, which then carried on its own monitoring program.

"The water quality has been pretty bad for ages," said Adrian Bostic, who volunteers with his teenage son taking water samples for the Potomac Riverkeeper Network. They live in Northeast Washington, near the banks of the Anacostia, and joined the effort as a down payment on future afternoons fishing close to home.



Potomac riverkeeper Dean Naujoks peers into one of Washington, D.C.'s 48 combined sewer outfalls. The John F. Kennedy Center for the Performing Arts is visible in the background. Credit: Mark Betancourt

Volunteers Adrian Bostic and his son, also named Adrian, collect water samples from the Potomac River. Credit: Mark Betancourt

"[We] might as well get involved and do what we can do to help clean it up. And maybe we can get to actually experience the water that's around us," Bostic said.

Dozens of volunteers like the Bostics are out every week during the summer, collecting samples and rushing them to the lab for analysis while the bacteria in them are still fresh.

"[We] might as well get involved and do what we can do to help clean it up. And maybe we can get to actually experience the water that's around us."

The Potomac Riverkeeper Network has its own lab aboard a repurposed fishing vessel. There, volunteers feed the collected bacteria a nutrient that causes them to change color—*Escherichia coli* glows under ultraviolet light. By dividing the water into rows of plastic bubbles, they can extrapolate the concentration of *E. coli* in the river by simply counting how many bubbles glow.

Later, volunteers upload the data to Chesapeake Monitoring Cooperative, where they're made publicly available to both the community and researchers. The data will also be shared with Swim Guide, a crowdsourced global network that lets users look up whether their waterway is safe for recreation. According to Naujoks, about 25,000 people in the D.C. area used the site last year.

Samples are collected on Wednesdays, so the results are ready by the weekend. That's when the largest crowds come out to kayak, fish, and—despite the law—swim.

Jeff Seltzer, a deputy director at DOEE, said the monitoring program is meant to warn residents when the water is especially unsafe, while also being a cost-effective way to shore up the city's understanding of bacteria in its waterways. "It builds constituency and educates the public about the issues around water quality, and leverages that interest to get us more data," he said.

To that end, D.C. has also partnered with the U.S. Geological Survey (USGS) on a new study that will lend scientifically reviewed methodology to future water quality alerts. Instrument stations at either end of the Anacostia will measure the water's temperature, specific conductivity, pH, dissolved oxygen, and turbidity. An automated in situ analyzer will allow the stations to determine bacterial loads without the need to send samples to a lab.

With continuous high-quality data, said principal investigator Jonathan Dillow, the USGS project aims to find the connections between water conditions and bacterial loads in the river. Warmer and more turbid water, for instance, is more hospitable to bacteria. But how these factors interact within the complicated flow of the Anacostia—the river is partially tidal, which means that Chesapeake Bay water periodically flushes upstream, both slowing and churning it—determines whether bacteria persist in some parts of the river and die off quickly in others. All of this matters when trying to determine the true impact of combined sewer overflows on the river's water quality.

"As far as I know, no one has successfully gone after the causality that might be reflected in the data that [have] been collected," said Dillow. "We're not going to capture the whole picture with our efforts, but we are going to capture more than we know right now."

The goal of the USGS project is to build a model that can forecast whether the river will be safe for recreation on a continuous basis. Anacostia Riverkeeper is collaborating with a company called DataRobot on a similar bacteria forecasting model using machine learning. The organization is feeding the model data from its volunteer programs and from the government's historical monitoring database.

The glut of new data, once readily available, could drive water quality policy across the region and allow local governments to concentrate their resources on the biggest problem areas.

Crumbling Infrastructure

Combined sewer overflows are not the only sources of bacteria in D.C.'s waterways. Two thirds of the city's sewer system has separate pipes for sewage and storm water, but in addition to surface runoff sources like pet and wild animal waste, bacteria can end up in the rivers through residential sewer lines that are illegally connected to the storm drain system. (The city is working on a project that uses DNA fingerprinting to identify whether bacteria found in the river come from human waste, which will allow the municipal government to identify and target illegal connections.)

And aging sewer pipes can break or leak. In a recent report, the American Society of Civil Engineers (ASCE) estimated that the city's average sewer main is more than 90 years old. Ray said DC Water's goal is to replace its aging sewer infrastructure at a rate of roughly 1% per year, although ASCE noted that the city is not yet meeting that goal and in fact needs to double it.

Bacteria are also coming from upstream. While communities in the Anacostia's upper watershed use separate sewer and storm drain systems, sewage can still make its way into the river's many tributaries. Erosion, sped by development, has exposed buried sewer lines, making them more likely to be damaged by hazards like falling trees.

During the September 2020 storm, the Northwest Branch Anacostia River, which flows past my neighborhood in Hyattsville, jumped its banks and invaded the little woods where I walk with my children. That night, there was so much sewage in the floodwater coming from upstream that my nostrils burned.

Anacostia Riverkeeper is expanding its monitoring program upstream to better understand all the contributors to the river's bacterial load. "As we start looking [in] more places, we keep finding more spots" where sewage is entering the watershed, said Anacostia riverkeeper Trey Sherard.

As part of a consent decree similar to the one that led to the Clean Rivers Project, WSSC Water, the sewer authority in the Maryland counties that make up more than 80% of the Anacostia watershed, has been gradually repairing, upgrading, or replacing its pipeline system.

"It's not just the DC Water project that is bearing fruit right now," said Sherard. "Across all 176 square miles of [watershed], almost that entire area is seeing significant sewer infrastructure improvement."

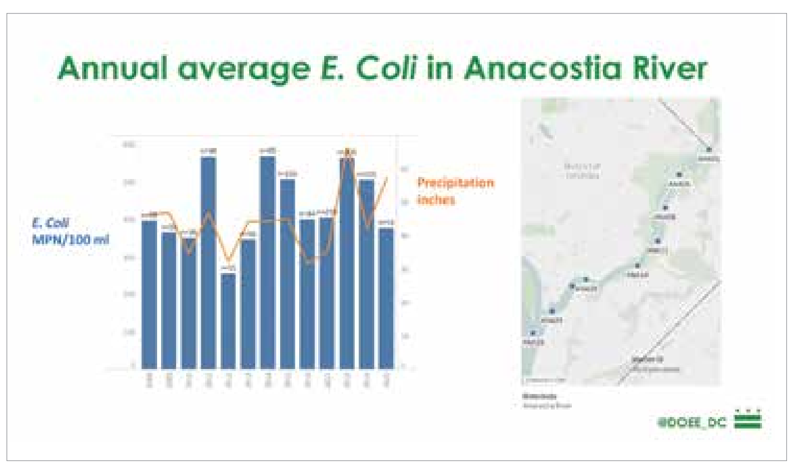
"We're not going to capture the whole picture with our efforts, but we are going to capture more than we know right now."

A Moving Target

But uncertainty looms over local optimism about swimmable rivers.

The year D.C. partnered with local organizations to do more frequent sampling of the rivers—the same year the first Clean Rivers tunnels came online—was also the wettest year on record in the District of Columbia. More than 167 centimeters (66 inches) of rain fell in 2018, 66 centimeters (26 inches) more than average. The city's operational deep tunnels captured 17 billion liters (4.5 billion gallons) of combined sewage overflow. But it wasn't enough.

"Even though you're keeping out billions of gallons [of sewage], with the biggest rainfall events in history, you're still getting significant input from the combined



Many factors contribute to bacterial loads in urban rivers, but this graph shows a loose correlation between precipitation and the most probable number (MPN) of E. coli bacteria, a strong indicator of sewage contamination. Credit: Washington, D.C., Department of Energy and Environment sewer system and other sources throughout the watershed,” said Seltzer.

And the deluges keep coming. During the September 2020 storm, rain came down so hard and fast that the tunnels—with a combined capacity of more than 378 million liters (100 million gallons)—overflowed in just over half an hour.

The U.S. Global Change Research Program has projected that heavy rain events in the Northeast and Midwest will become more intense and more frequent by the end of the century. The heaviest 1% of events could produce at least 40% more precipitation. Nature is going to be hurling increasingly massive amounts of water onto cities with combined sewer systems, and keeping sewage out of waterways is going to get harder.

Darren Olson, vice chair of ASCE’s Committee on America’s Infrastructure, pointed out that many sewage overflow tunnel systems were designed in the 1970s and 1980s—quite a way back on the climate hockey stick. “What we’re finding with a lot of these systems that were planned decades ago [is that] by the time they get built, according to today’s standards, they could be undersized,” Olson said.

“We’re Trying to Make Sure That We’re Thinking This Out”

Milwaukee may be a bellwether. Its deep tunnel system was completed in 1993 and has been expanded twice. The system has had a huge impact on CSOs, cutting the number of overflow events from more than 50 per year to only two or three. But Milwaukee riverkeeper Cheryl Nenn said that 2018 and 2019 broke rainfall records in the city. It’s too early to tell exactly what effect that’s having on water quality, but there has been a recent uptick in the volume of sewage overflowing into Milwaukee’s rivers. “That was a real eye-opener here,” Nenn said. “We had not seen numbers like that in quite a while.”

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The key to keeping up with ever increasing precipitation is to transform the urban surface itself.

The key to keeping up with ever increasing precipitation, Olson said, is to transform the urban surface itself. Rain gardens, bioswales, and other measures to encourage water infiltration can take the pressure off deep tunnels by capturing rain where it falls, rather than funneling it into the combined sewer system in the first place.

D.C. is already undertaking some of those green infrastructure projects, and Ray said the tunnel system was designed to be expanded, including room for more pumps and treatment facilities to process sewage more quickly. “We’re trying to make sure that we’re thinking this out,” he said. “Not just 20 years out—a hundred years out.”

Even with such measures, said Olson, some coastal cities could see their sewer systems overwhelmed not by rain but by storm surges. “When you’ve got your sea level rising and all your storm sewers are draining out into that same body that’s rising, these storm sewers become even less effective at carrying water,” he said. Even upriver cities like D.C. are vulnerable to rising sea levels and tidal flooding. And once combined sewer systems start taking on seawater, no storage tunnel will be big enough to contain the overflow.

Despite warnings that the Anacostia is regularly contaminated with raw sewage, thousands of residents boat, fish, and swim in D.C.’s rivers each year. Credit: Mark Betancourt

For now, D.C.’s main problem is rain, and more is on the way. The storage capacity of the Clean Rivers tunnels was based on rainfall data from 1988 to 1990; the picture those data painted is sure to shift. “If those historic rainfalls are increasing dramatically, as we predict they will,” said Seltzer, “then we’ll likely get more overflows than we had planned on.”

That’s where the community monitoring programs the city is sponsoring could become even more essential, especially if the city lifts its swimming ban. “We’ll have more days where we would just simply have to put out warnings and restrict swimming,” said Seltzer.

Naujoks, the Potomac riverkeeper, hopes D.C.’s system is big enough to handle what’s coming. Next year is the fiftieth anniversary of the Clean Water Act, and he wants the city to understand that even 50 years from now, the law’s goal of giving Americans back their waterways will not have changed. He plans to make sure that the Clean Water Act is honored in the nation’s capital.

“There’s constant vigilance,” he said. “That’s the role of a water keeper.”

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Filling the Gaps in the SuperDARN Archive

The Super Dual Auroral Radar Network tracks ionospheric plasma circulation from the ground, including auroral activity like this in Estonia. Credit: Kristian Pikner, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

When solar wind slams into Earth's magnetic field, the impacts ripple down through the planet's ionosphere, the outer shell of the atmosphere full of charged particles. A global array of high-frequency radars known as the Super Dual Auroral Radar Network (SuperDARN) tracks ionospheric plasma circulation from the ground, giving researchers insights into the interactions between solar wind, the magnetosphere, and the ionosphere. Though widely used in space physics research, the network is not comprehensive—each ground-based radar can measure plasma velocity only in its line-of-sight direction, for example. As a result, there are major spatial and temporal gaps in the SuperDARN archive.

Historically, researchers have filled in these gaps with models that make assumptions based either on climatological averages of the SuperDARN data or on solar wind measurements. In a new study, *Shore et al.* present a new method using a data-interpolating empirical orthogonal function technique, which allows researchers to detect patterns within existing SuperDARN plasma velocity data and then use this information to fill in gaps. The team used observations collected by the network's Northern Hemisphere stations in February 2001 and filled in missing information at any given time using the velocity patterns deduced from data collected at a given location throughout the month and from other network locations at the same time.

The SuperDARN data set is critical for understanding space weather and its potential impacts on the technologies underlying things like radio communications and satellite services, and this new technique can provide researchers with the most accurate estimates yet of ionospheric electrodynamic variability. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2021JA029272, 2021) **—Kate Wheeling,** *Science Writer*

Volcanic Tremor and Deformation at Kīlauea

Kīlauea in Hawaii is the best-monitored volcano in the world. The 2018 eruption was the largest in some 200 years, providing researchers with a plethora of new data to understand the volcano's plumbing and behavior. Two new studies dig into data on volcanic tremor and deformation to better characterize the events leading up to and following the 2018 eruption.

In one study, *Soubestre et al.* used data from a permanent seismic network and tiltmeter located at Kīlauea's summit and derived models of tremor source processes to examine how volcanic tremors related to the disappearance of a lava lake and subsidence in Halema`uma`u Crater at the beginning and throughout the 2018 eruption. Here the authors used a seismic network covariance matrix approach to enhance coherent signals and cut out noise to detect and locate the volcanic tremor sources.

The team identified three previously unidentified tremor sources, including long-period tremor during the period preceding the eruption associated with radiation from a shallow hydrothermal system on the southwestern flank of Halema`uma`u Crater. The team picked up on two sets of gliding tremor in early and late May. Models show that the first set was linked to the intrusion of a rock piston into the hydrothermal system, and the second was linked to changes in the gas content of magma within a dike below the crater affected by a dozen collapse events.

The second study focused on the period following the 2018 eruption. Here *Wang et al.* used GPS and interferometric synthetic aperture radar data to examine deformation around the caldera associated with the volcano's known reservoirs—the shallow Halema`uma`u (HMM) reservoir and the deeper South Caldera (SC) reservoir—after the eruption ended in August of 2018. They documented inflation on the northwestern side of the caldera and deflation on the southeastern side of the caldera, indicating that the summit magma chambers are hydraulically distinct. The concurrent East Rift Zone (ERZ) inflation indicated dynamic magma transfer between the summit and the ERZ.

The authors presented a new physics-based model that uses differential equations to describe reservoir pressure and magma flux between the volcano's reservoirs to simulate potential magmatic pathways of connectivity between the reservoirs and the ERZ. They used a dynamic inversion of the postcollapse GPS time series of surface displacement to estimate the conductivity of potential magmatic pathways.

The team found that the primary connective pathway in the postcollapse period that best fits the GPS data is a shallow connection between the HMM reservoir and the ERZ. The study doesn't rule out a direct pathway between the SC reservoir and the ERZ but suggests that if it exists, it was significantly less active over the study period.

Together these studies help to create an increasingly clear picture of the plumbing and processes governing Kīlauea's activity in 2018. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2020JB021572 and https://doi.org/10.1029/2021JB021803, 2021) **—Kate Wheeling,** *Science Writer*

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Satellite Sensor EPIC Detects Aerosols in Earth's Atmosphere

Aerosols are small, solid particles that drift aloft in Earth's atmosphere. These minuscule motes may be any of a number of diverse substances, such as dust, pollution, or wildfire smoke. By absorbing or scattering sunlight, aerosols influence Earth's climate. They also affect air quality and human health.

Accurate observations of aerosols are necessary to study their impact. As demonstrated by *Ahn et al.*, the Earth Polychromatic Imaging Camera (EPIC) sensor on board the Deep Space Climate Observatory (DSCOVR) satellite provides new opportunities for monitoring these particles.

Launched in 2015, DSCOVR's orbit keeps it suspended between Earth and the Sun, so EPIC can capture images of Earth in continuous daylight—both in the visible-light range and at ultraviolet (UV) and near-infrared wavelengths. The EPIC near-UV aerosol algorithm (EPICAERUV) can then glean more specific information about aerosol properties from the images.

Like other satellite-borne aerosol sensors, EPIC enables observation of aerosols in geographic locations that are difficult to access with ground- or aircraft-based sensors. However, unlike other satellite sensors that can take measurements only once per day, EPIC's unique orbit allows it to collect aerosol data for the entire sunlit side of Earth up to 20 times per day.

To demonstrate EPIC's capabilities, the researchers used EPICAERUV to evaluate various properties of the aerosols it observed, including characteristics known as optical depth, single-scattering albedo, above-cloud aerosol optical depth, and ultraviolet aerosol index. These properties are key for monitoring aerosols and their impact. The analysis showed that EPIC's observations of these properties compared favorably with those from ground- and aircraft-based sensors.

The research team also used EPIC to evaluate the characteristics of smoke plumes produced by recent wildfires in North America, including extensive fires in British Columbia in 2017, California's 2018 Mendocino Complex Fire, and numerous North American fires in 2020. EPIC contributed to the observational proof of smoke self-lofting via the tropopause by solar absorption-driven diabatic heating in 2017. EPIC observations successfully captured these huge aerosol plumes, and the derived plume characteristics aligned accurately with ground-based measurements.

This research suggests that despite coarse spatial resolution and potentially large errors under certain viewing conditions, EPIC can serve as a useful tool for aerosol monitoring. Future efforts will aim to improve the EPICAERUV algorithm to boost accuracy. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2020JD033651, 2021) **—Sarah Stanley,** *Science Writer*

How Long Do Black Carbon Particles Linger in the Atmosphere?

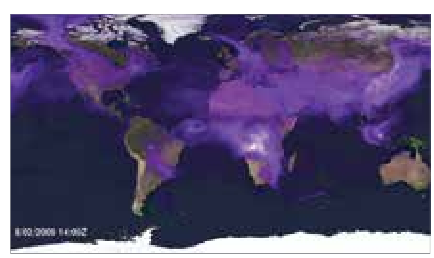
There's a stubborn, heat-absorbing particle that floats along in Earth's atmosphere: It initially doesn't like water, it absorbs light, and it takes its time moving on. Black carbon in the atmosphere tends to linger until it finally absorbs enough water to fall from the sky. In the meantime, black carbon absorbs the Sun's energy and heats up surrounding air, creating a radiative effect.

Fresh, young black carbon tends to be resistant to water. Over time, the particles age and become more hygroscopic, or able to absorb water from the air. But when does black carbon start absorbing water, act as cloud nuclei, and remove itself from the atmosphere?

Researchers previously investigated hygroscopic conditions of black carbon in the lab, placing limits on chemical sources and water vapor. In these studies, the cloud nucleation values of black carbon were indirect measurements.

In a new study by *Hu et al.*, researchers concurrently measured the concentration of cloud condensation nuclei and black carbon particles. The sampling site was near heavily trafficked roads and industrial centers in Wuhan, China, an urban megacity in the central part of the country.

They first corrected for the size of particles, then measured cloud condensation nuclei and individual black carbon particles in certain levels of water supersaturation in the atmosphere. The team found that the activation diameter, or the size of the black carbon particle where half of the particles will nucleate and precipitate out, was 144 ± 21 nanometers at 0.2% supersaturation. How these black carbon-containing particles could act as cloud nuclei is determined by their size combined with their coatings, the authors say, and in general, the less saturated the air was, the bigger the particles had to be to nucleate.



Black carbon particles are spread throughout our atmosphere, produced by the burning of fuels or industrial processes. Credit: NASA Goddard Space Flight Center's Scientific Visualization Studio

In addition, the team found that a particle itself may influence the size of nucleation. For instance, the amount of organic content in a particle or any coating on the black carbon can change the hygroscopicity and therefore the activation.

The research team noted that their work can help improve estimates of the longevity of suspended black carbon particles in the atmosphere and therefore the radiative impacts those particles can have. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2021JD034649, 2021) **—Sarah Derouin,** *Science Writer*

Examining the Intricacies of Ozone Removal by Deciduous Forests

Deciduous forests are important sinks of ozone in the part of the atmosphere closest to Earth, where the molecule is an air pollutant injurious to humans and plants, as well as a greenhouse gas. Credit: Freerange Stock

Ozone plays a vital role in Earth's climate system. In the stratosphere, which begins about 6 miles (9.7 kilometers) off the ground, ozone protects the planet from harmful ultraviolet radiation. Lower in the atmosphere, however, the molecule is an air pollutant injurious to both humans and plants, as well as a greenhouse gas.

Ozone interacts with forests through a process known as dry deposition, often with harmful consequences. In this process, turbulence in the atmospheric boundary layer brings ozone to the surface where reactions on and inside leaves and soil remove ozone from the air. Ozone injury to plants results from ozone reactions inside leaves and can alter carbon and water cycling.

The mechanics of dry deposition are not completely understood, however. While we know that turbulent eddies in the atmosphere transport ozone to surfaces onto which the gas can be deposited, one remaining question is whether the organized nature of these eddies, known as organized turbulence, influences dry deposition. Uncertainty related to the mechanics of dry deposition makes it harder to understand ozone in the lower atmosphere and ozone's impacts on both plants and humans.

In a new study, *Clifton and Patton* use high-resolution computer simulations to examine the relationship between turbulent eddies and leaf ozone uptake. The authors hypothesized that organized turbulence generates local fluctuations in temperature, wind, and humidity that together with local changes in ozone might result in different rates of ozone uptake by leaves. They call this variation in leaf uptake "segregation of dry deposition." By taking segregation of dry deposition into account, scientists can better predict ozone dry deposition, the authors say.

The results showed that organized turbulence did not create more efficient areas of ozone uptake in the forest canopy. In other words, higher concentrations of ozone in some air motions together with higher leaf uptake in the same air motions did not result in more ozone uptake by the canopy. Therefore, the findings are a null result and indicate that segregation of dry deposition is likely an unimportant factor in a forest's ozone budget. Null results despite commonly being perceived as insignificant, play an essential role in figuring out important natural processes. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006362, 2021) **—Aaron Sidder,** *Science Writer*

Is Venus Volcanically Active? A New Approach Could Provide an Answer

A novel method for studying lava flows on Venus indicates that some flows associated with the 9-kilometer-tall volcano Maat Mons (shown here with an exaggerated vertical scale) may be relatively young—in line with the possibility that the planet is still volcanically active. Credit: NASA/JPL

Of all the planets in the solar system, Venus has the most volcanoes. Much of the planet is covered in volcanic deposits that are less than 300 million years old, and volcanic activity has played a pivotal role in its history. Although the precise timeline of Venus's volcanic past is still debated and some data suggest that the planet may still have active volcanoes, the evidence remains inconclusive.

For multiple reasons, researchers have had difficulty determining whether there are active volcanoes on Venus. The planet's atmosphere is corrosive and features high pressures and temperatures—above 450°C (842°F)—that make it inhospitable for the kinds of spacecraft that can last for years on Mars or the Moon. Meanwhile, thick clouds of sulfuric acid limit visible observation of the planet's surface, so researchers have turned to other remote measurements, including radar collected by NASA's Magellan spacecraft, to map it.

According to *D'Incecco et al.*, a new methodology could finally help solve the mysteries of volcanic activity on Venus. As applied in a recent study, this approach combines geologic mapping of cooled lava flows from past eruptions with additional radar data from the Magellan mission. Specifically, it relies on measurements of the planet's radar emissivity—a measure of how its surface interacts with and emits microwave radiation.

Different parts of Venus's surface have different levels of emissivity that correspond to different properties of rocks, providing clues to their composition. In particular, recent research suggests that radar emissivity can be used to determine the degree of chemical weathering experienced by lava flows after they erupt and contact the planet's harsh atmosphere. Such weathering happens over weeks or months, so emissivity could potentially help identify fresh lava flows.

The authors combined radar emissivity measurements with geologic mapping to compare three Venusian volcanoes: Maat Mons, Ozza Mons, and Sapas Mons. Their findings suggest that some lava flows at Maat Mons might be relatively young.

In the future, the same approach could be applied to additional Magellan data to further explore Venus's volcanism. The methodology could also be important for future Venus missions that will provide higher-resolution radar emissivity measurements, including the European Space Agency's EnVision mission and NASA's Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission.

Alongside information from additional upcoming missions, including NASA's DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging) mission and the Venera-D mission, the new strategy could finally help reveal which, if any, of Venus's volcanoes are still active, as well as provide new insights into the planet's volcanic past. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2021JE006909, 2021) **—Sarah Stanley,** *Science Writer*

Tibetan Plateau Lakes as Heat Flux Hot Spots

The largest alpine lake system in the world sits atop the Qinghai-Tibet Plateau, commonly known as the Tibetan Plateau, which is the highest and largest plateau in the world. Researchers know that the lakes influence the transfer of heat between the land and the atmosphere, affecting regional temperatures and precipitation. But little is known about the physical properties and thermal dynamics of Tibetan lakes, especially during the winter months when the lakes are covered in ice.

In a new study, *Kirillin et al.* looked at China's Ngoring Lake—the largest freshwater lake (610 square kilometers) on the plateau—which is typically covered in ice from December through mid-April. The team moored temperature, pressure, and radiation loggers in one of the deepest parts of the lake in September 2015. They observed an anomalous warming trend after the lake surface froze over, as solar radiation at the surface warmed the upper water layers under the ice. Strong convective mixing left Ngoring Lake fully mixed down to its mean depth within a month of full ice cover.

In most ice-topped lakes, water temperatures typically remain below the maximum density temperature, but here the authors found that the water temperature was higher than the maximum freshwater density by the middle of the ice season, which accelerated the ice melt at the end of the winter season. As the ice broke up, water temperature dropped by nearly 1°C, releasing some 500 watts per square meter of heat into the atmosphere in just 1 or 2 days.

Ice covers Ngoring Lake, the largest freshwater lake on the Tibetan Plateau. Credit: Tom Shatwell

The study demonstrates that lakes do not lie dormant under ice and that their effects extend beyond their boundaries; taken together, the thousands of lakes across the plateau could be heat flux hot spots after ice melt, releasing the heat absorbed from solar radiation and driving changes in temperatures, convection, and water mass flux with potential impacts at even global scales. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL093429, 2021) **—Kate Wheeling,** *Science Writer*

Understanding Aurora Formation with ESA's Cluster Mission

Earth's aurorae form when charged particles from the magnetosphere strike molecules in the atmosphere, energizing or even ionizing them. As the molecules relax to the ground state, they emit a photon of visible light in a characteristic color. These colliding particles—largely electrons—are accelerated by localized electric fields parallel to the local magnetic field occurring in a region spanning several Earth radii.

Evidence of these electric fields has been provided by sounding rocket and spacecraft missions dating to as far back as the 1960s, yet no definitive formation mechanism has been accepted. To properly discriminate between a number of hypotheses, researchers need a better understanding of the spatial and temporal distribution and evolution of these fields. When the European Space Agency's (ESA) Cluster mission lowered its perigee in 2008, these observations became possible.

Cluster consists of four identical spacecraft, flying with separations that can vary from tens of kilometers to tens of thousands. Simultaneous observations between the four craft enable space physicists to deduce the 3D structure of the electric field.

Marklund and Lindqvist collect and summarize the contributions of Cluster to our understanding of the auroral acceleration region (AAR), the area of space in which the above-described processes take place.

By collecting a large number of Cluster transits through this region, physicists have deduced that the AAR can generally be found somewhere between 1 and 4.4 Earth radii above the surface, with the bulk of the acceleration taking place in the lower third. Despite this relatively broad "statistical AAR," the acceleration region at any given moment is usually thin; in one observation, for example, the AAR was confined to an altitude range of 0.4 Earth radius, whereas the actual layer was likely much thinner than that. The observations cannot uniquely determine the thickness of the actual layer, which could be as small as the order of 1 kilometer, the authors say. Such structures are observed to remain stable for minutes at a time.

Cluster measurements also have shed light on the connection between the observed shape of the electron acceleration potential and the underlying plasma environment. So-called S-shaped potentials arise in the presence of sharp plasma density transitions, whereas U-shaped ones are related to more diffuse boundaries. However, the dynamic nature of space plasma means that the morphology of a boundary can shift on timescales of minutes, as exemplified by a case study.

In sum, 2 decades of Cluster observations have significantly improved our understanding of the processes—both local and broad—that result in our planet's beautiful aurorae. With the missions extended through 2022, we can expect more insight in the coming years. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2021JA029497, 2021) **—Morgan Rehnberg,** *Science Writer*

Tree Rings Show Record of Newly Identified Extreme Solar Activity Event

Growth rings are visible here on an unknown tree species at Bristol Zoo in the United Kingdom. Tree rings record environmental conditions in the year they form. Credit: Arpingstone/Wikimedia, Public Domain

The Sun constantly emits a stream of energetic particles, some of which reach Earth. The density and energy of this stream form the basis of space weather, which can interfere with the operation of satellites and other spacecraft. A key unresolved question in the field is the frequency with which the Sun emits bursts of energetic particles strong enough to disable or destroy space-based electronics.

One promising avenue for determining the rate of such events is the dendrochronological record. This approach relies on the process by which a solar energetic particle (SEP) strikes the atmosphere, causing a chain reaction that results in the production of an atom of carbon-14. This atom subsequently can be incorporated into the structure of a tree; thus, the concentration of carbon-14 atoms in a tree ring can indicate the impact rate of SEPs in a given year.

To date, three events of extreme SEP production are well described in literature, occurring approximately in the years 660 BCE, 774–775 CE, and 992–993 CE. Each event was roughly an order of magnitude stronger than any measured in the space exploration era. *Miyake et al.* describe such an event, which occurred between 5411 BCE and 5410 BCE. Because of this burst, atmospheric carbon-14 increased by 0.6% year over year in the Northern Hemisphere and was sustained for several years before dropping to typical levels.

The authors deduced the presence of this event by using samples collected from trees in three widely dispersed locales: a bristlecone pine in California, a Scotch pine in Finland, and a European larch in Switzerland. Each sample had its individual tree rings separated, and material from each ring underwent accelerator mass spectrometry to determine its carbon-14 content.

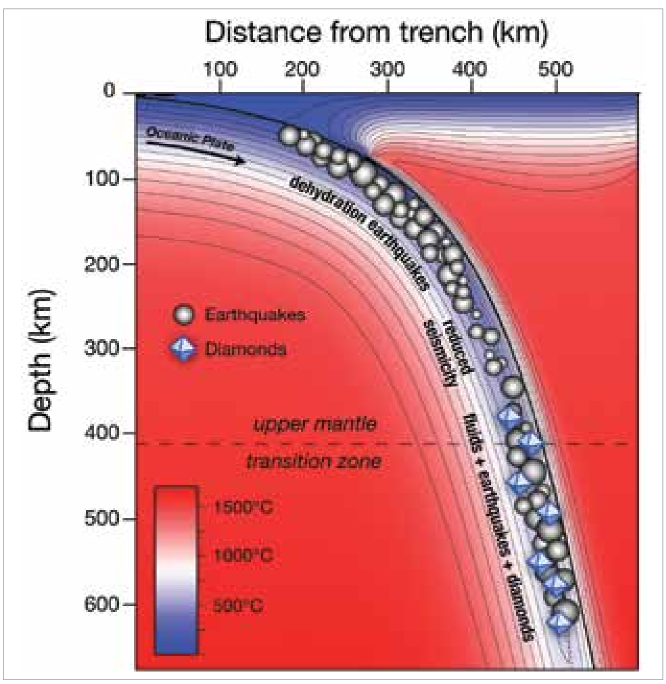
Using statistical methods, the researchers identified a pattern of small carbon-14 fluctuations consistent with the Sun's 11-year solar cycle; the event recorded in the tree ring occurred during a time of solar maximum. Notably, other evidence suggests that the Sun was also undergoing a decades-long period of increasing activity.

If an extreme SEP burst is indeed the cause of the additional carbon-14, then these observations could aid in forecasting future events. However, tree ring measurements cannot rule out other extraterrestrial causes, such as a nearby supernova explosion. Confirmation will require isotopic measurements of beryllium and chlorine taken from ice cores, according to the authors. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL093419, 2021)
—Morgan Rehnberg, *Science Writer*

Diamonds Are at Fault

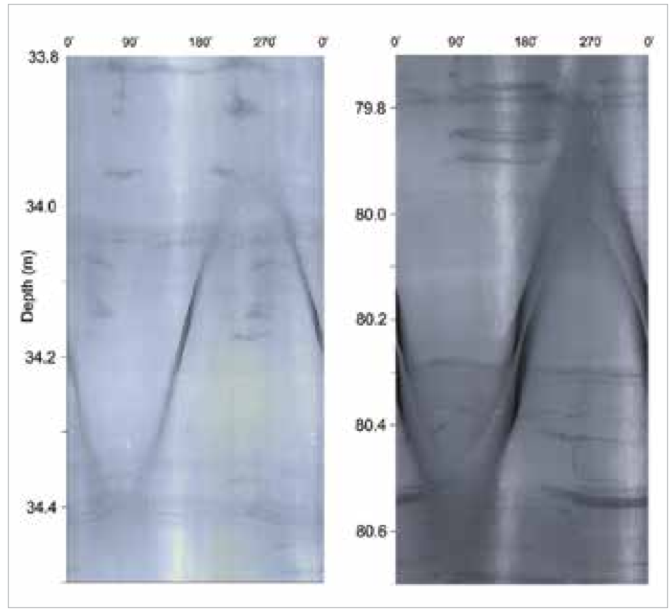
Deep earthquakes represent brittle failure of rock in a regime that is generally ductile, and the mechanism that causes these earthquakes below 300 kilometers is debated. Proposed mechanisms for deep earthquakes include a delayed phase transition of olivine at depth, development of weakness zones associated with spinel transitions, and a potential role for fluids. Hydrous minerals and carbonates can be carried down by the subducted slab to depths below 300 kilometers.

Shirey et al. provide the first convincing arguments that reactions that liberate fluid or melt occur at the focus of deep earthquakes. These arguments are based on observations of the mineral assemblage of inclusions in deep sublithospheric diamonds, which are the deepest samples from Earth's mantle that we have, and on phase equilibria modeling. Thermodynamic models combined with thermal models of downgoing slabs show that carbon- or hydrogen-containing mineral phases will release their volatiles at depth and can form some of the largest diamonds found. Inclusions in diamonds record their depth of formation, which coincides with the depth where deep earthquakes occur. The authors propose that the release of these fluids triggers the deep seismicity. (https://doi.org/10.1029/2020AV000304, 2021) **—Vincent Salters**



A sample thermal model of a subduction zone shows the relatively cold (blue) oceanic plate sinking into the comparatively hot (red) mantle. Three regions of earthquakes (gray spheres) are visible in the oceanic plate: "intermediate depth" dehydration-related earthquakes occurring at about 70–250 kilometers depth, a region of reduced seismicity at approximately 250–350 kilometers depth, and the region of "deep" seismicity below 350 kilometers that extends to a depth of about 700 kilometers. Superdeep diamonds (blue octahedra) are known to crystallize from fluids released in this deep region as the oceanic plate warms from the heat of the surrounding mantle. Credit: Illustration by Steven Shirey, Peter van Keken, Lara Wagner, and Michael Walter/Carnegie Institution for Science

Crevasses Transport Heat Deep into Greenland Ice



These images show several identified crevasse traces from depths of approximately 34 meters (left) and approximately 80 meters (right) in the core. In this 2D representation of the 360° borehole image, the traces are identifiable as distinct sinusoids cutting other (horizontal) ice layers at a high angle; in 3D space, they are steeply dipping planes. The layers are formed of bright (bubble-rich) laminae, enveloped on each side by centimeter-thick layers of dark (bubble-poor) ice. These are interpreted as freezing water filling a crack in the ice several centimeters thick, with air expelled upon freezing accumulating in the central zone. Credit: Hubbard et al.

Newly available optical technology has provided the first direct observations of crevasse traces in a borehole drilled in Store Glacier, a fast moving outlet glacier of the Greenland Ice Sheet. *Hubbard et al.* have recognized these traces as distinctive zones of steeply inclined layers with bubble-rich and bubble-free ice zones. These features are explained as crevasses that opened, filled with water, and then refroze, sometimes repeatedly in the same place. What is surprising is that the crevasse traces are observed up to 265 meters deep in the borehole, whereas increased ice temperatures suggest that water and the heat it carries penetrate up to 400 meters deep, deeper than previously assumed. An implication of this discovery is that such deep crevasse traces can survive advection to the ice front, where they can be an important determiner of patterns of ice calving and rifting. (https://doi.org/10.1029/2020AV000291, 2021) **—Susan Trumbore**

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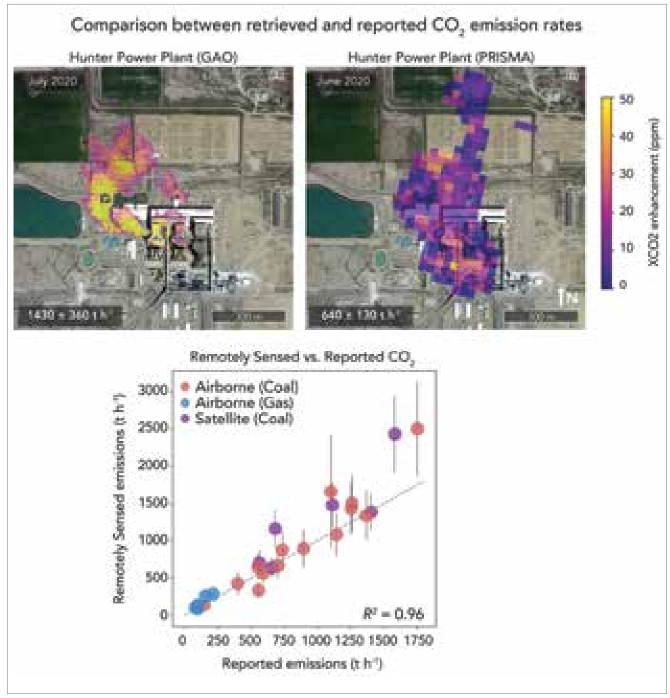
Constraining Global Power Plant Emissions of Carbon Dioxide

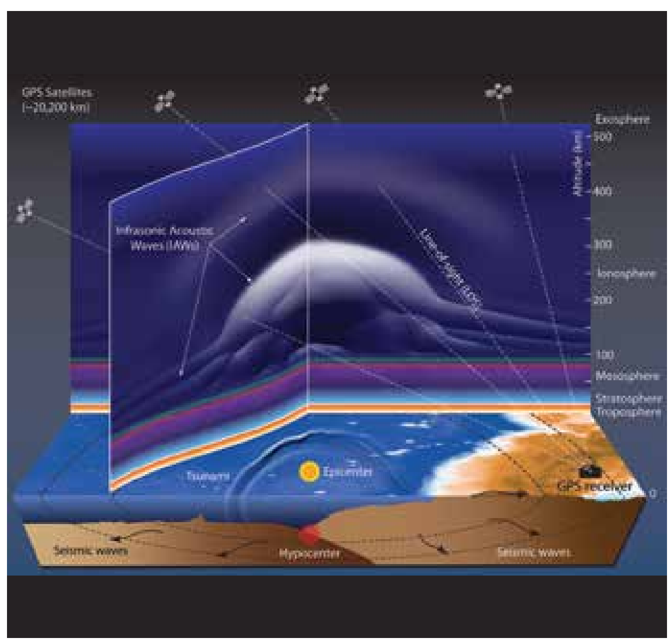
Carbon dioxide (CO_2) emissions from power plants represents one of the largest sources of greenhouse gases from humans. Keeping track of CO_2 emissions from all global power plants is difficult, as the availabililty of reliable emissions data can depend on a country's emission reporting protocols. However, remote sensing with imaging spectrometer instruments offers a new capability to do top-down monitoring. The instruments provide high spatial resolution CO_2 plume maps that can be used to quantify emissions. *Cusworth et al.* show examples where CO_2 emissions are quantified and validated at 21 global gas- and coal-fired power plants using airborne and satellite imaging spectrometers. The authors estimate that with repeated targeting by satellites, 60% of all global power plant emissions could be tracked. This capability is key to reducing uncertainties in global anthropogenic CO_2 emission budgets and supporting emissions mitigation strategies. (https://doi.org/10.1029/2020AV000350, 2021) **—Donald Wuebbles**



Comparison between retrieved carbon dioxide (CO_2) emission rates and those reported by the U.S. Environmental Protection Agency (EPA). The top row shows a comparison between retrieved CO_2 plumes from an airborne instrument (GAO; left) and the PRISMA satellite at the coal-fired Hunter Power Plant in Utah (right), overlaid on a Google Earth image. In the bottom panel, a scatterplot compares power plant emissions remotely sensed by airborne and satellite instruments to EPA Continuous Emissions Monitoring (CEMS) reports. The dashed gray line represents the one-to-one line. Credit: Cusworth et al.

Earthquake Rupture Solution Is Up in the Air

On 14 November 2016, a magnitude 7.8 earthquake struck New Zealand's South Island. This earthquake occurred on multiple faults and is considered one of the most complex ruptures ever recorded. The near-simultaneous breakage of 12–20 faults that trend in multiple directions and are offset by significant distances makes the earthquake's slip distribution challenging to fully characterize. Multiple data types—including seismological, geodetic, and geological—are needed for this characterization. *Inchin et al.* add another novel data layer by using observations of infrasonic acoustic waves detected in GPS signals to model the earthquake-induced disturbances that created the waves. The authors performed computationally intensive modeling of ionospheric disturbances and determined that for their modeling to match the observations, an additional fault (Papatea) must have been activated in the already complex rupture. (https://doi.org/10.1029/2020AV000260, 2021) **—Tom Parsons**



Earthquake-induced infrasonic acoustic waves are generated at solid-air or water-air interfaces. These waves propagate to the upper layers of the atmosphere and generate ionospheric plasma disturbances, which can be detected by analysis of GPS signal degradation driven by ionospheric plasma. Modeling these observations can yield details about the crustal disturbances that generated them, helping to constrain the rupture process. Credit: Inchin et al.

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Dartmouth Engineering seeks to fill a tenure-track faculty position at the Assistant or Associate level in the field of polar physical oceanography. This position is part of a thriving multidisciplinary academic cluster in Arctic Engineering in a period of Climate Change, and will promote convergent science within Dartmouth, including the Thayer School of Engineering, Earth Sciences, Geography, the Institute for Arctic Studies and Dartmouth's Arthur L. Irving Institute for Energy and Society.

The successful candidate will have a doctorate in engineering or a related science field and demonstrated potential to lead an externally funded research program pursuing transformational advances in our understanding of the effect of climate change on ocean interactions with sea ice and land ice. Candidates with fieldwork experience are particularly encouraged to apply. The candidate will be a gifted teacher with motivation and expertise that complements the Thayer School's interdisciplinary approach to engineering education.

Applicants should submit a cover letter, complete CV, research statement, statement of teaching interests and philosophy, and three reference letters or contact information for three references.

We are committed to building a culture of inclusion, and we invite applicants to provide a statement of their experiences and contributions to inclusion and diversity within their cover letter.

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GEOMAR
Helmholtz Centre for Ocean Research Kiel

C|A|U
Christian-Albrechts-Universität zu Kiel

Kiel University and GEOMAR Helmholtz Centre for Ocean Research Kiel aim to attract more qualified women to professorships.

The Faculty of Mathematics and Natural Sciences at Kiel University, Germany and GEOMAR Helmholtz Centre for Ocean Research Kiel jointly invite applications for a

limited term W 2-Professorship (six years) tenure track in Theoretical Oceanography

to start at the earliest possible time.

The Professorship is based at GEOMAR Helmholtz Centre for Ocean Research Kiel and assigned to the Research Unit 'Ocean Dynamics' within the Department 'Ocean Circulation and Climate Dynamics'.

The professor will represent the fields oceanography and climate dynamics in research and teaching.

We are seeking a candidate with an excellent and international research profile in physical oceanography and climate dynamics. Applicants shall be dynamic and team players, and bring future research concepts in one or more of the following or equivalent fields: Geophysical Fluid Dynamics (GFD); ocean-atmosphere exchange; process understanding of the oceanic turbulence and mixing, as well as their parameterizations; combining models and observations with assimilation; methods of data science or artificial intelligence in the physical marine sciences. The successful candidate can build on a well-established cooperation between modelling and observational ocean and climate research groups. We particularly expect interdisciplinary cooperation with other GEOMAR departments and within Kiel Marine Sciences and informatics.

The professor will teach within the Kiel B.Sc. and M.Sc. programs in ocean and climate physics. We expect teaching in English. Non-German speaking applicants are expected to acquire German language skills and to teach some courses in German after three years at the latest. Please refer to the recruitment requirements of § 61 of the Higher Education Act of the State of Schleswig-Holstein.

After successful evaluation and if the additional requirements of § 62 of the Higher Education Act of the State of Schleswig-Holstein are met, the aim is to grant tenure in the professorship. To this end at Kiel University, in accordance with the current statutes, an evaluation procedure is carried out, usually one year before the limited professorship ends. More information can be found at www.berufungen.uni-kiel.de (in German). For additional information about the position and the research unit please contact Prof. Dr. Arne Biastoch (abiastoch@geomar.de).

Kiel University and GEOMAR Helmholtz Centre for Ocean Research Kiel are striving to increase the number of female scientists in research and teaching and therefore expressly encourages qualified women to apply. Women will be given priority if their aptitude, qualifications and professional performance are equal.

The University and GEOMAR are committed to the employment of severely disabled people. For this reason, severely disabled applicants will be given preferential treatment if they have the appropriate qualifications. We welcome applications from people with a migration background. Application photographs are not required and we request that you to refrain from submitting any.

Applications in English with the usual documents (cover letter, curriculum vitae, copies of academic certificates, lists of publications, courses taught and third-party funding, teaching concept, research plan) along with your private and business address, telephone number and e-mail address should be sent in electronic form (preferably in electronic form as a single PDF file to berufungen@mnf.uni-kiel.de) to the following address by **November 21, 2021: The Dean, Faculty of Mathematics and Natural Sciences, Kiel University, D-24098 Kiel, Germany.**

Hello, Everyone!

I am pictured here with my colleague Diana Saqui, gathering data in the shadow of the majestic Antisana volcano in Ecuador.

On this field trip, we carried out an active geophysical survey using multichannel analysis of surface waves to get an image of the subsurface structure and stratigraphy of the area. These activities support the research project Linking Global Change with Soil and Water Conservation in the High Andes–ParamoSus, which aims to contribute to sustainable ecosystem management in the High Andes by conducting evidence-based research on the interactions among soil, water, and vegetation across different spatiotemporal scales.

The ParamoSus project, funded by the Académie de Recherche et d'Enseignement Supérieur in Belgium, is a joint initiative of several companies, a water fund, and four academic institutions, including Escuela Politécnica Nacional.

More information on the project can be found at bit.ly/ParamoSus.

Best wishes!

—**Juan Gabriel Barros L.,** Instituto Geofísico de la Escuela Politécnica Nacional, Quito, Ecuador

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12–16 December 2022
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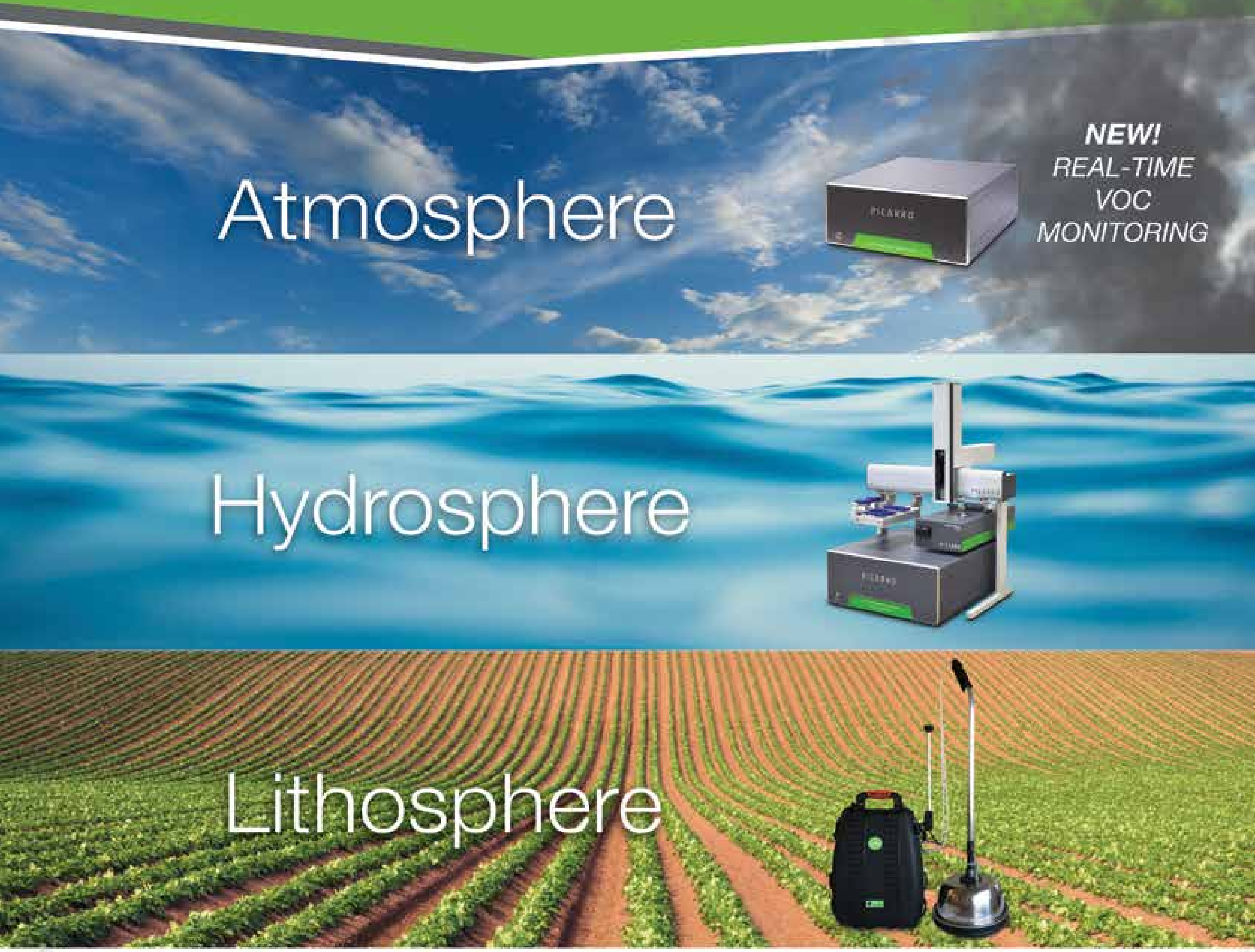

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