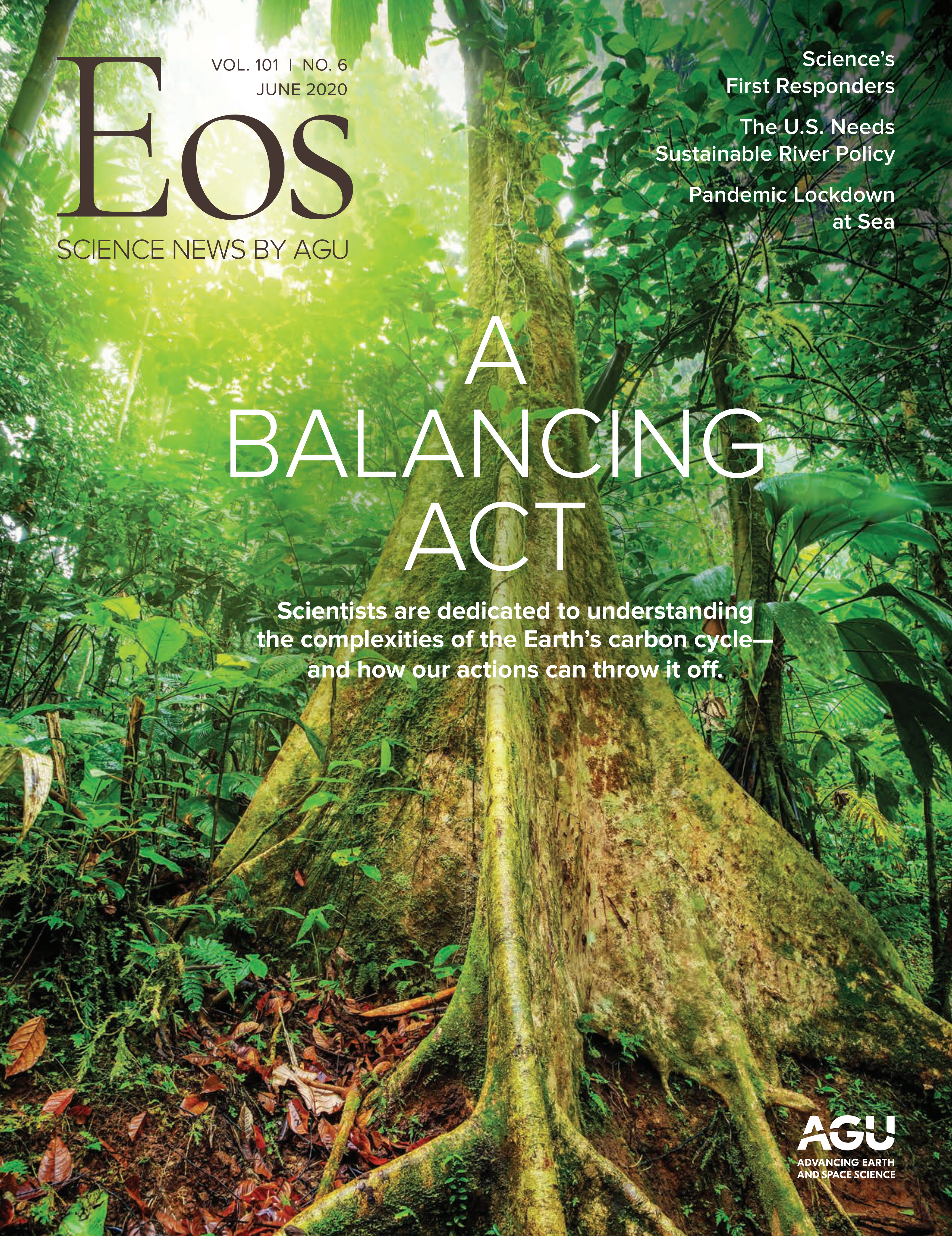


Eos

VOL. 101 | NO. 6
JUNE 2020

SCIENCE NEWS BY AGU

Science's First Responders

The U.S. Needs Sustainable River Policy

Pandemic Lockdown at Sea

A BALANCING ACT

Scientists are dedicated to understanding the complexities of the Earth's carbon cycle—and how our actions can throw it off.

AGU
ADVANCING EARTH AND SPACE SCIENCE

A Whole World View

The livability of our world depends on a healthy circulatory system for carbon. Knowing how carbon transitions among air, land, and sea is critical to understanding the balance that keeps Earth habitable—not to mention, understanding how our actions can throw off that balance.

In our June issue, several science teams report on work in this area. In "The Future of the Carbon Cycle" (p. 34), Aleya Kaushik and colleagues discuss the complexities of gaining a whole-world view of that cycle. Achieving this holistic view challenges our understanding of how ecosystems respond to climate change and how those responses will alter Earth's carbon budget in the future. In particular, these predictions are complicated by the numerous feedbacks involved. Kaushik et al. look to the observation networks—both on the ground and orbiting overhead—that have evolved over the past several decades to help scientists address these critical questions.

On p. 22, Donato Giovannelli and colleagues consider the carbon cycle at subduction zones, specifically, at the Costa Rica convergent margin. This multidisciplinary team was part of a project under the Deep Carbon Observatory called Biology Meets Subduction, which was aimed at answering several questions about the influence of biological activity at the convergent margin and, ultimately, determining whether the team could use that information to improve deep-carbon budget estimates for the area. Like all the best research, their work is yielding promising data and raising many more intriguing questions.

In this month's news, we report on a fascinating experiment at a geothermal facility in Iceland. Carbon storage trials are showing that 90% of carbon dioxide injected into subsurface basalt rock is transformed into minerals in just 2 years, whereas mineralization in standard carbon storage methods can take thousands of years. Turn to p. 6 to read more about the potential of mineral carbonation as a means of large-scale carbon sequestration in Iceland and elsewhere and whether it's up to the task of making a measurable impact on climate change.

On the other side of the carbon cycle, a recent study shows that mountain streams, though comprising only about 5% of the surface area of rivers and streams globally, might account for 10% to 30% of the total flux of carbon dioxide from those waterways (p. 14). Scientists have also recently discovered that the Arctic Ocean may not be as important a carbon sink as previously thought (p. 11).

Finally, we're pleased to share an article from the editor in chief of one of AGU's newest journals, *GeoHealth,* on p. 17. Gabriel Filippelli writes in "Geohealth: Science's First Responders" about how geoscientists, health professionals, and regional leaders are growing into a new community that is combining and harnessing its skills to address disasters. Looking back at the Deepwater Horizon disaster and the Tohoku earthquake and tsunami, Filippelli examines lessons learned from those events and how we should be applying them to the current global pandemic.

Our June issue examines the balance of this planet's systems and, in so many ways, how anthropogenic forcing can step on that balance. How can we assess the natural movements of carbon while we keep pumping carbon into the air? How can we prepare to live safely in a world where disasters, even relatively predictable ones, can still be sudden and overwhelming? The scientists featured in this issue are committed to answering those questions and, ultimately, to making our world more knowable so we can better prepare ourselves for change.

Heather Goss, Editor in Chief

Eos
AGU ADVANCING EARTH AND SPACE SCIENCE

Eos (ISSN 0096-3941) is published monthly by AGU, 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 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.

Submit your article proposal or suggest a news story to *Eos* at bit.ly/Eos-proposal.

CONTENT

Features

On the Cover

Trees in the lush rainforest of Costa Rica and elsewhere play an important role in the carbon cycle. Credit: Anna Omelchenko/ Alamy Stock Photo

Columns

From the Editor

News

Opinion

AGU News

Research Spotlight

Editors' Highlights

Positions Available

Postcards from the Field

AmericanGeophysicalUnion @AGU_Eos company/american-geophysical-union AGUvideos americangeophysicalunion americangeophysicalunion

How Financial Markets Can Grow More Climate Savvy

Energy investors looking to steel themselves against topsy-turvy market transitions could try something new: factoring extreme weather risks into their investments.

At present, financial markets may be failing to account for the physical risks of extreme weather from climate change. That's a problem, according to Paul Griffin, an accounting professor at the University of California, Davis, because overpricing could lead to an extreme correction to the market down the road.

On the other hand, if markets do adjust and societies reduce emissions, "a couple of generations from now, we might have a more stable planet," Griffin said. "This is something that will benefit generations beyond ourselves."

Although researchers are just starting to understand possible links between market pressures of the coronavirus crisis and the climate crisis, Griffin said that lessons learned may help with climate-related transitions. Crude oil prices plunged below zero in April, and the pandemic has revealed weaknesses in global supply chains.

But unlike the market's "forward-looking" response to the pandemic, the costs associated with climate change "are far more distant," and the markets have a "tough time" grappling with them, Griffin said. In the long term, addressing climate risks "is much more important than what we're going through now," he added.

Invisible Risks

Energy firms are at particular physical risk due to climate change, yet they've been slow to price these risks.

Many energy firms have infrastructure in vulnerable areas. The U.S. Gulf Coast, where numerous oil refineries are located, is facing rising seas and more extreme storms. Southern states are also seeing skyrocketing temperatures, which threaten worker safety. California and other western states are exposed to arid air and wildfires, causing power disruptions.

Despite these vulnerabilities, investors and asset managers have been "conspicuously slow to connect physical climate risk to company market valuations," Griffin wrote. Company stock prices do not reflect these risks, and it's unclear whether insurance will provide coverage. Future litigation could also prove costly.

"This is an issue that needs to be addressed, so the markets correct themselves in a reasonable or orderly basis," Griffin said. If they don't, a correction all at once "can be very horrific for markets."

The Great Recession is the "best analogy" to the present situation, according to Griffin. A sudden correction to the market from unpriced risk in subprime mortgages kicked off the financial crisis in 2007, which in turn triggered the Great Recession that rippled around the world.

A market adjustment and reducing emissions are things "that will benefit generations beyond ourselves."

Making a Shift

To avoid a large market correction from extreme weather impacts, investors need to pin down the exact risk from future events. Extreme weather risks pose a unique challenge for climate risk modelers because some investors normalize extreme weather impacts over time. Some emerging companies, like Jupiter Intelligence and Four Twenty Seven, could work to fill this gap, and others could work to make data digestible for investors and asset managers.

Recently, Norway's Government Pension Fund Global divested part of its fossil fuel holdings, and the Saudi Aramco corporation began offering some public shares. "For investors and asset managers, the Norwegian and Saudi actions are a further sign of climate risk underpricing," Griffin wrote in his comment in the journal *Nature Energy* (bit.ly/energy-finance).

Jesse Keenan, an associate professor of real estate at Tulane University, said that the shift could help markets bear the risks of future transitions as well. "Advancing more disclosure on the physical risks (e.g., generation facilities, transmission equipment, etc.) could be catalytic for forcing greater analysis of the transition risks, which are closely interconnected," noted Keenan.

Factoring climate change into market decisions is difficult, said Griffin, because "you've got these massive costs that are far more distant that the markets have a really hard time grappling with." Moving forward will take both political will and a responsive judicial system, he added.

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

Dust from Colliding Asteroids Masqueraded as a Planet

Planets don't normally triple in size, but that's what Fomalhaut b seemingly did.

Originally heralded as an extrasolar planet, this object probably isn't a planet after all, researchers have now suggested. By analyzing unpublished Hubble Space Telescope data, scientists have shown that it's more likely an expanding cloud of dust created by a catastrophic collision between large asteroids. Given that such impacts should be exceedingly rare—occurring only once every few hundred thousand years, the team calculated—this discovery was downright lucky.

An Oddball

In 2008, astronomers announced the discovery of Fomalhaut b orbiting a star roughly 25 light-years away. It joined a rarefied club: The object was one of a handful of exoplanets that had been directly imaged (as opposed to being detected using the transit method or the radial velocity method, for instance). But Fomalhaut b had some distinctly unplanetlike characteristics: It didn't emit thermal radiation, for starters, and it was growing significantly in size. "Fomalhaut b has always been enigmatic," said András Gáspár, an astronomer at Steward Observatory at the University of Arizona.

To better pin down the nature of Fomalhaut b, Gáspár and George Rieke, also an astronomer at Steward Observatory, mined archival data from the Hubble Space Telescope. They collected observations of Fomalhaut b obtained from 2004 to 2014, including unpublished data from 2013 and 2014.

Expanding and Going Sideways

Gáspár and Rieke found that Fomalhaut b resembled a point source—as expected for a distant planet—in observations from 2004 and 2006. But in the next data set, collected in 2010, it had ballooned in size and now looked like a cloud. Between 2004 and 2014, Fomalhaut b expanded by roughly 7,500,000 kilometers, or about 5% of the Earth-Sun distance, per year, the researchers calculated. "That's pretty quick," said Gáspár.

Fomalhaut b's position in the sky was also odd, the scientists found. Rather than swinging around its host star in a planetlike elliptical orbit, "its trajectory is leading radially away from the central star," said Gáspár.

Dust to the Rescue

These decidedly unplanetlike characteristics led Gáspár and Rieke back to an idea proposed earlier by other researchers: Fomalhaut b is not a planet but, instead, an expanding cloud of dust. This seemingly unorthodox hypothesis is consistent with its bizarre properties: A dust cloud would reflect lots of optical light from its host star but wouldn't produce much of its own thermal radiation, an expanding cloud would explain Fomalhaut b's threefold increase in size, and a dust cloud would appear to move radially away from a star because the smallest and lightest dust particles are literally blown outward by starlight.

Catastrophic collisions between asteroids create copious amounts of dust. Credit: NASA/JPL-Caltech

The dust probably derived from a collision of asteroids, astronomers have proposed. And the Fomalhaut system doesn't lack for asteroids; it's known to host a dusty debris disk, an amalgam of dust and small rocky bodies akin to our own solar system's asteroid belt and Kuiper belt.

Gáspár and Rieke modeled asteroid impacts and their resulting dust clouds. They calculated that two asteroids roughly 200 kilometers in diameter smashing together could have produced Fomalhaut b. On the basis of the estimated density of asteroids near Fomalhaut's debris disk, such an event would statistically occur every few hundred thousand years, the team estimated. These results were published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/Fomalhaut).

Because the Fomalhaut system is about 400 million years old, it's exceedingly unlikely that we'd be witness to such an event.

Too Rare?

"A collision between objects is a fairly natural explanation," said Grant Kennedy, an astronomer at the University of Warwick in the United Kingdom not involved in the research. "It's pretty hard to create a puff of dust...in any other way."

But the likelihood of such a collision might be far lower than what Gáspár and Rieke estimate, Kennedy cautioned. "Previous calculations have suggested that the frequency of collisions between objects that are about 100 kilometers in size is very, very low, fewer than one in the age of the system." Because the Fomalhaut system is about 400 million years old, it's exceedingly unlikely that we'd be witness to such an event, said Kennedy. "People will no doubt revisit this analysis, just like they did for the original Fomalhaut b discovery."

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

Opposite: Unsplash/Michelle Henderson

Basalts Turn Carbon into Stone for Permanent Storage

Iceland's Hellisheiði Geothermal Power Station, above, is the third-largest geothermal power station in the world and the site of ongoing mineral carbonization experiments. Credit: Árni Sæberg

In carbon storage experiments tied to geothermal power plants in Iceland, 90% of injected carbon dioxide (CO_2) transformed into minerals in just 2 years. Standard carbon storage methods can take thousands of years to do the same.

"We are basing our methods on this natural process, which is part of the big carbon cycle where all carbon on Earth derives from and ends up in rocks," said one of the lead researchers, Sandra Snæbjörnsdóttir. She is the head of CO_2 mineral storage at the CarbFix project.

"By mineralizing, we are permanently getting rid of the CO_2. We can walk away from it. We don't have to monitor it for the next decades or so. The permanent storage is the key here," she said.

"By mineralizing, we are permanently getting rid of the CO_2. We can walk away from it."

Fast and Forever

The Intergovernmental Panel on Climate Change reported that to keep global warming below 1.5°C, humanity must not only drastically cut CO_2 emissions but also actively remove CO_2 from the atmosphere and keep it locked away. Most ongoing carbon capture and storage (CCS) projects seal captured CO_2 deep underground in sedimentary rock reservoirs to keep it from escaping. That carbon eventually seeps into small rock pores, dissolves in groundwater, and reacts with the rock to become carbonate minerals, trapping the carbon for good.

However, this method alone can't store a large enough volume of carbon or mineralize it fast enough to meet the carbon storage demand. It can take thousands of years from start to finish for all of the carbon to mineralize, and at any point, a shift in the rocks can cause some carbon to escape.

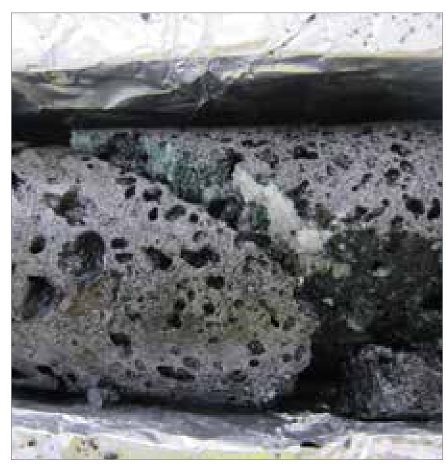
Climate researchers have long recognized that highly reactive basaltic rocks could be a solution to the carbon storage problem. In addition to being common around the world, basalts contain high concentrations of calcium and magnesium ions that chemically react with CO_2 to make calcite, dolomite, and magnesite. Moreover, dissolving the CO_2 in water above ground and then injecting it into subsurface basalts bypasses the slower and less secure stages of conventional carbon storage.

Geothermal power stations, which sit atop basalt-rich volcano deposits, were a natural site for the new method's first field tests. Since 2012, the CarbFix project has partnered with Iceland's Hellisheiði Geothermal Power Station to capture the CO_2 released when drawing up hot water from the ground. The team dissolves the CO_2 in wastewater and injects it hundreds of meters deep into the basaltic ground. The risk of induced seismicity is reduced by carefully surveying injection sites and adjusting injection rates as needed.

Snæbjörnsdóttir and her team have been examining the injection sites using fluid sampling and tracers to quantify how well the mineral carbonization process works. They found that over 90% of the injected CO_2 had been converted into minerals within 2 years of injection.

"We have demonstrated a very rapid mineralization of the injected gases," she said. "But also, the way that we inject is that we dissolve the CO_2 in water prior to or during injection.…The CO_2-charged fluid is heavier than the groundwater in the formation where we are injecting, so it has the tendency to sink rather than to rise up. This increased storage security."

The team published these results in *Nature Reviews Earth and Environment* (bit.ly/CO2-stone).



Carbon dioxide dissolved in water reacted with the basalt (black) in this core to create carbonates (white), trapping the carbon in solid form deep beneath the ground. Credit: Sandra Ó. Snæbjörnsdóttir

Expanding Around the Globe

Mineral carbonization has been gaining interest in recent years, Snæbjörnsdóttir said. "People often believe that this can only be done if you have geothermal [heat], but that's not the case," she said. "The things that you need for this to work are just a source of CO_2, [water], and reactive rocks."

A team in the United States found that the flood basalts of the Columbia River have a similar mineralization rate. The European Union has sponsored future versions of CarbFix, and an international consortium has formed with the goal of using CCS to lower geothermal emissions.

Snæbjörnsdóttir's team is currently working to combine this process with direct air capture of CO_2 and researching other pathways to mineral carbonization.

"We know that basalts like we have here in Iceland are perfect for this method," she said, "but there might be rock types that are less reactive but still reactive enough. If some of those rock types are feasible to use for this method, we could broaden the applicability even more."

"By using this method, you can store CO_2 in areas you had not considered before."

"For example, there's been a lot of work done in Oman where they have very reactive peridotites in connection with the ophiolites that are there," she said.

The team is also looking into how well offshore injections using seawater might work. Offshore injection would make this method an option in regions with limited freshwater resources or that might be prone to induced seismicity. If combined with direct air capture of CO_2, that could also bring this carbon storage method to areas that aren't strong CO_2 emitters.

"It expands the applicability of CCS in general, because by using this method you can store CO_2 in areas you had not considered before," Snæbjörnsdóttir said. "You're opening up new possibilities in addition to the conventional CCS that is already taking place."

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

Nonscientists Struggle to Separate Climate Fact from Fiction

iStock.com/Olivier Le Moal

Can you recognize the truthfulness of simple statements about climate change? Are you sure about that?

A recent study asked 500 nonscientists to verify whether climate change statements were true or false and how confident they were that science agreed with them. The researchers found that nonscientists were underconfident in their knowledge of true statements about climate change but were overconfident in their ability to recognize statements as false.

"The confidence we have in our knowledge directs our decisions," said Helen Fischer, a postdoctoral researcher in environmental cognition at the Stockholm Resilience Centre in Sweden. "If you have correct knowledge but you are not confident in that knowledge, then the accuracy of your knowledge doesn't help. We need to be confident that it is correct to base our decisions on it."

Conversely, "if you have incorrect knowledge, this is doubly bad if you have high, unwarranted confidence in that knowledge, because then you will base decisions on wrong knowledge. We will make unfounded decisions." These results were published in *Nature Climate Change* (bit.ly/climate-change-knowledge).

Unwarranted Self-Doubt

The degree to which confidence in knowledge is matched by the accuracy of that knowledge is known as confidence accuracy. "For example," the team wrote, "rejecting the statement that natural variation in sunbeams is the main driver of climate change shows accurate knowledge, but being uncertain about this rejection shows inaccurate confidence. Accepting the statement that greenhouse gas emissions are a main driver of climate change shows accurate knowledge, and being certain about this acceptance also shows accurate confidence."

Confidence accuracy can be a powerful tool to assess people's understanding in areas of knowledge that, like climate change, are rife with misinformation. The researchers measured the confidence accuracy with regard to climate change of nonscientists in Germany by presenting them with statements about the state, sources, and consequences of climate change. For each statement, a person was asked whether science agrees with the statement and to rate their level of confidence in their answer from guessing (50% confidence) to absolutely certain (100% confidence).

For comparison, the team asked more than 200 climate scientists the same climate change questions and a different group of nonscientists questions about physical and biological sciences. These comparisons revealed how high nonscientists' confidence accuracy *could* be with regular exposure to scientifically valid information and how high their confidence *should* be given their confidence in a similar topic.

The researchers found no significant difference in nonscientists' confidence accuracy with regard to the state, sources, or consequences of climate change. "The most striking result," Fischer said, "is how bad [nonscientist] citizens are at telling what they

"For the false statements, citizens appeared to have no insight into the fact that they did not know."

know and what they do not know about climate change compared with how good they are at telling what they know and do not know when it comes to general science."

On true statements, nonscientists' confidence in their climate change knowledge was only about half what it could be on the basis of the accuracy of that knowledge—they knew the right answer but didn't trust that they did. This doubt was greater than for nonscientists' general science knowledge and for climate scientists' knowledge.

However, nonscientists sometimes were unable to verify 60% of the false statements about climate change yet were very confident that they had done so. This trend was seen only for nonscientists on climate change.

Even when considering that someone might just know more about physics or biology than about climate change, nonscientists were "disproportionately bad" at assessing the limits of their climate knowledge, Fischer said. "For the false statements," the team wrote, "citizens appeared to have no insight into the fact that they did not know."

Katharine Hayhoe, a climate scientist at Texas Tech University in Lubbock, said that "while the first half of the results of this study are encouraging—that people were able to correctly identify true statements and felt confident about their ability to do so—the second half of this study—that they were not as able to identify the false statements even when they felt confident in their answers—is discouraging but not surprising." Hayhoe was not involved with this research.

The Impact of Misinformation

"There is no question that misinformation increases people's uncertainty regarding what is and what is not true," Hayhoe said. "When strong statements are made by perceived experts or thought leaders who we respect, we tend to assume they are true. Today, however, we are being fed false information about climate change on a near-daily basis."

Fischer noted that this research tested only German citizens and that the results might be different in countries with different educational, political, and media landscapes. She aims through future research to assess whether confidence in climate change knowledge correlates with belief in climate change, how people's confidence differs before and after their exposure to misinformation, and how that confidence changes over a long period of time.

"There has been a large, long-lasting effort to criticize the science of climate change," said climate researcher Richard Alley of Pennsylvania State University in University Park, who was not involved with this study. "There is scholarship...showing that so-called 'skeptical' scientists have greater public exposure than mainstream scientists, so that the public message received by a large fraction of the population is that scientific uncertainty and scientific debate are much larger than they really are."

"If people are not confident that scientists agree," Alley said, "it might not be surprising that people are not confident of their own understanding."

"If we appear very confident, this affects others," Fischer said. "This is very risky. If someone has low knowledge but high confidence, then this will influence others, and then wrong climate change knowledge can have strong network effects, for example, with the media or the Internet."

Although this study was not able to assess the degree to which misinformation about climate change led to the true-false gap in confidence accuracy, she said, it did underscore an important point: "The take-home message is that increasing knowledge is not enough," she said. "What has been done a lot is to try and increase citizens' knowledge about climate change. Now the knowledge is out there. [People's] knowledge is not so bad."

"The next step is to increase confidence," Fischer said, "not just in accurate statements but also such that people know what is true and what is untrue with high confidence. So that when they see a false statement, they confidently know, 'No. I know very certainly this is false.'"

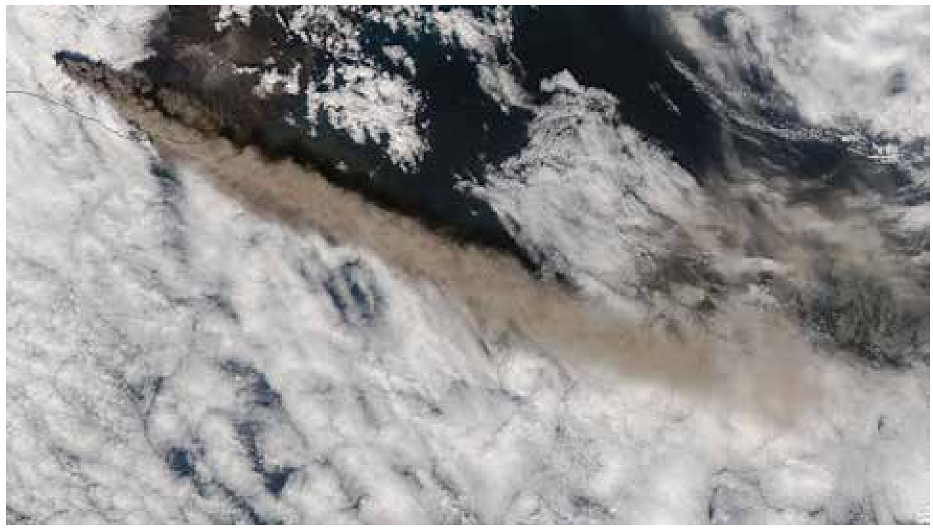
By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

The Art of Volcanic Ash Modeling 10 Years After Eyjafjallajökull

On 14 April 2010, the Icelandic volcano Eyjafjallajökull erupted explosively, hurling volcanic ash several kilometers into the atmosphere. Northerly winds then blew this dense plume toward Europe and the busiest airspace in the world. Over the next 6 days, hundreds of thousands of flights were canceled.

In the first week of the eruption, the closing of European airspace led to the loss of 1.3 billion euros (approximately $1.4 billion). In an attempt to stop the hemorrhaging, European aviation regulators turned to models of ash dispersal to determine where the plume was less dense and unlikely to damage aircraft engines.

Scientists had only started to develop such models, however, and relied on knowing intricate details about the eruption to perform the work. "But in 2010, the amount and quality of the information about ongoing volcanic activity at the beginning of the eruption were quite low," said volcanologist Sara Barsotti of the Icelandic Meteorological Office.



A plume of ash from Eyjafjallajökull volcano in Iceland extends across the sky 4 weeks after the 14 April 2010 eruption. Credit: NASA/GSFC/Jeff Schmaltz/MODIS Land Rapid Response Team, CC BY 2.0 (bit.ly/ccby2-0)

Moreover, European regulators decided that planes could fly on routes where the ash was below a certain level, but the modelers weren't confident that their models could deliver the necessary degree of accuracy at each point of the journey, said Larry Mastin, a hydrologist at the U.S. Geological Survey (USGS) in Vancouver, Wash.

The 2010 experience, however, galvanized the community into creating more powerful models. "It became a technical challenge for the world's modelers to be able to produce model output during an eruption that has meaningful airborne ash concentrations," Mastin said.

Shattered Glass

Despite its name, volcanic ash isn't the remains of burned material, like the ash left after fires. It is far more deadly.

As magma rises underneath a volcano, tiny bubbles of carbon dioxide and water vapor form in it. When the magma can no longer hold the bubbles, they pop, driving the volcanic eruption. And once the sticky bubble walls reach the atmosphere, they cool into tiny shards of glass, each less than a few millimeters in size.

Most of the ash from Eyjafjallajökull consisted of these bubble fragments, but ash can also be produced from the shattering of old rock during the eruption or can include mineral fragments that are contained in the magma. The tiny shards of broken bubbles are what typically cause the most damage to humans as well as planes, however.

"If you're in a place that's having heavy ashfall, it either forms cement in your lungs, which isn't good, or it cuts your lungs," said Erik Klemetti, a volcanologist at Denison University in Granville, Ohio. "As gruesome as it sounds, the deaths from volcanic ash are usually coming from people drowning in their own blood."

Consequently, in the early 2000s, researchers around the world began to try to forecast where ash would travel or fall after an eruption. While in Italy, Barsotti helped develop the model in 2008, and by 2010, the USGS had developed its own model called Ash3d.

"By April 2010, it was just starting to work, and then of course, Eyjafjallajökull erupted," said Mastin. "And then the whole world changed in terms of how important it was to be able to forecast where ash clouds go."

A Meeting of Minds

In the early 1990s, the International Civil Aviation Organization began to set up nine Volcanic Ash Advisory Centers (VAACs) around the world to monitor and provide warnings to aircraft of volcanic ash in their region. Early on, the operators would scan satellite images to look for ash clouds, or once they heard of an eruption, they'd set their own rudimentary models running.

But to accurately model ash dispersal, the VAACs needed vital details on an eruption such as the height of the plume, the time the eruption started, and how long the eruption lasted. Consequently, volcanologists became involved, and the collaborations spurred improvements to the meteorological dispersion models used by most VAACs, along with development of volcano-specific models such as Ash3d.

When trying to determine how far ash travels, a key factor is how much ash is "coming out of the box" during an eruption, a quantity that is correlated with the height of the plume, Mastin said. Another important factor is the grain size of the ash that is being erupted—smaller particles remain aloft longer and can drift farther.

Wind patterns determine how fast and how far the ash is transported, requiring the input of hour-by-hour meteorological data at different heights and distances from the volcano. "The way that ashes are dispersed in the atmosphere is pretty complicated," Mastin said. "It could be blowing in a completely different direction at several kilometers' altitude than it is at low altitude."

The VAACs have their own models, which they use to generate specialized warnings to the aviation community; researchers, volcano observatories, and weather services around the world are able to freely use Ash3d to generate ashfall warnings from eruptions in their region.

In Iceland, researchers now use the Numerical Atmospheric-dispersion Modelling Environment (NAME) ash dispersal model, developed by the UK Met Office, integrated into a system that models a range of impacts expected from an eruption. The Icelandic Meteorological Office is continuously running simulations of eruptions of five high-threat volcanoes using current weather conditions with this software. "Having this system in place helps a quick response to an emergency," Barsotti said.

Onward and Upward

Although researchers have improved their models in the past 12 years, techniques used to monitor many of the features of an eruption have also advanced, which also increases the models' accuracy, Barsotti said.

Monitoring volcanoes for eruptions is essential to providing timely warnings, and even remote volcanoes that are under air traffic routes need to be monitored, said volcanologist Charles Mandeville, program coordinator of the USGS Volcano Hazards Program.

In March 2019, legislators passed a bill to fund the National Volcano Early Warning System in the United States, which will eventually result in increased monitoring of high- and medium-risk volcanoes in the country. "We have to get much better at optimizing the networks that are out on the volcanoes, to give us the earliest warnings possible," Mandeville said.

The fact that modelers now have increased access to better quality monitoring data, as well as the opportunity to assimilate the observational data into the models, has improved their forecasts a lot, Barsotti said. But ultimately, the biggest advancements in the past 10 years have come from the collaborations between scientists from many different disciplines.

"The volcanological community is now connected with the meteorological community, for example," Barsotti said. "These connections will allow us to respond to the next eruption in a more workable and successful way."

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

Predicting Fast Moving Flash Droughts

Droughts have an insidious reputation, often building gradually over several dry seasons. Flash droughts are a lesser known phenomenon in which intensely dry conditions develop in as little as 2 weeks, wreaking havoc on crops and water supplies. A new study is shedding light on how scientists can more effectively monitor and predict these quickly evolving phenomena, which are projected to become more frequent with climate change.

Drought can devastate agricultural production. Credit: Unsplash/Christophe Maertens

Flash droughts were first recognized in 2002, but "we don't know much about how they develop because few studies have focused specifically on short-term events," said lead author Angeline Pendergrass, an atmospheric scientist at the National Center for Atmospheric Research in Boulder, Colo.

In the new study, published in *Nature Climate Change,* Pendergrass and colleagues define flash droughts as sudden onset events that create severely dry conditions in about 2–6 weeks (bit.ly/flash-droughts). If these events occur during the peak of the growing season, they can kill off crops over large areas, as happened across the midwestern United States in 2012.

The conditions leading up to a flash drought are still being quantified, but decreased rainfall, above-average temperatures, and low soil moisture all play a role, with many flash droughts triggered by heat waves following a dry period. Like regular droughts, flash droughts can strike anywhere, although arid and semiarid environments are especially susceptible because soils there often have low moisture levels year-round, Pendergrass said.

More work is needed to elucidate a myriad of other factors that may also contribute to flash droughts, she said, including the atmospheric and meteorological conditions that lead to decreased rainfall patterns, how the land surface responds to warmer temperatures, and the balance between water absorption and runoff in capturing the rain that does fall on a parched landscape.

Adapting Early-Warning Systems

Drought early-warning systems are already in place across the United States, said Donald Wilhite, a drought management specialist at the University of Nebraska-Lincoln, but these systems will need to be adapted to be able to predict droughts that evolve over short time frames. Wilhite was not involved in the new study.

"A comprehensive early-warning system is not just about tracking precipitation and temperature," he said. "You also need to monitor soil moisture conditions, streamflow, water stress, and reservoir levels."

Currently, these variables tend to be monitored on a weekly basis, with some factors updating more or less often, Pendergrass said. "We need to increase the frequency with which monitoring products are being updated so we can better capture these quickly moving flash drought events," she said. "[It] will take time, money, and people to accomplish that, but it's possible."

Both droughts and flash droughts are expected to occur more frequently and with more severity in the future, Wilhite said. "With climate change, temperatures are escalating, increasing water stress over large areas of the planet. We're seeing droughts run the gamut from weeks to multiple years, affecting entire continents. It's a hugely dynamic phenomenon."

The new study, authored by 22 people in fields ranging from atmospheric science to agricultural management, shows that flash droughts are becoming a more mainstream area of study, Wilhite said. "The authorship on this study is a good sign that flash droughts are being widely recognized by the scientific community. It's a very impressive cross-disciplinary collaboration, and that's what's needed to better understand these quickly moving drought events."

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

The Arctic Ocean May Not Be a Reliable Carbon Sink

Historically, scientists have believed that the Arctic Ocean will be an important carbon sink in the coming years: ice melt will increase the surface area that's exposed to the air, facilitating carbon uptake from the atmosphere, and cold Arctic waters can store more carbon dioxide (CO_2) than warmer waters.

Or at least that's what was supposed to happen. But scientists have begun to suspect that this might not be the case, and new research suggests that the Arctic Ocean, in fact, is not as reliable a carbon sink as we thought (bit.ly/Arctic-carbon). Using data from three research cruises (in 1994, 2005, and 2015), scientists were able to chart how the physical properties of the Arctic Ocean (including total alkalinity, temperature, and dissolved inorganic carbon) changed over time.

They found that over the past 20 years, although the amount of CO_2 in the atmosphere has gone up, the amount of dissolved inorganic carbon in Arctic waters has unexpectedly decreased.

That's because a reduction in sea ice isn't the only major change that's happening in the Arctic Ocean.

"There's actually been a huge increase of fresh water into the Arctic Ocean," said Ryan Woosley, a marine physical chemist at the Massachusetts Institute of Technology and lead author of the study. "The Arctic is kind of unique compared to the other oceans because there's a huge amount of river input compared to the size of the ocean…and fresh water has a very low alkalinity or buffering capacity, so this has reduced the ability of the Arctic Ocean to take up CO_2."

Over the past 20 years, the amount of dissolved inorganic carbon in Arctic waters has unexpectedly decreased.

But Manfredi Manizza, a biogeochemical oceanographer at the Scripps Institution of Oceanography, said that although there has indeed been an increased input of fresh water to the Arctic Ocean, the reasons for the less-than-expected uptake of anthropogenic carbon may be slightly more complicated than the explanation presented in the paper. He said that rivers have different alkalinities and carry different amounts of dissolved inorganic carbon into the Arctic Ocean, so understanding these inputs is an important part of determining the ability of the Arctic to take up atmospheric CO_2. Furthermore, there are many other changes taking place in the Arctic at the same time, each of which could also affect the ability of the ocean to take up CO_2.

A research vessel floats in the Arctic Ocean. Credit: NOAA

"There could be other pieces of the story that we don't know about yet," Manizza said. "There are so many physical and biogeochemical processes that are linked together that determine the [CO_2] uptake in the end."

Manizza pointed out that temperature is increasing rapidly in the Arctic Ocean—much faster than in the other oceans. And changing temperatures are associated with a whole suite of other changes: Sea ice is melting, removing a protective barrier between the ocean and the wind, which could affect ocean stratification. Warmer temperatures and changes in ocean stratification could affect the amount and the types of primary producers that can live in the Arctic. All of these factors, either directly or indirectly, may affect the amount of CO_2 that the Arctic Ocean can absorb from the atmosphere.

Arctic Freshening

However, Manizza agreed that Arctic freshening is occurring, which could have major implications for Arctic Ocean ecosystems.

"The fresh water and this lowering alkalinity are causing a rapid decrease in pH," said Woosley. This means that like many other oceans, the Arctic is becoming more acidic.

Although the effects of Arctic Ocean acidification are not fully understood, Manizza said that acidification could alter the types of plankton that are able to survive there, which could in turn affect organisms higher up the food chain. There are even concerns that acidification could threaten economically important Arctic fisheries.

Furthermore, Woosley said that an Arctic Ocean that is an ineffective carbon sink could have important global implications. "More [CO_2] will stay in the atmosphere, increasing global warming."

Ultimately, Woosley and Manizza agree that more data are needed. Woosley is hoping that another research cruise will take place in 2025, which would help to expand our knowledge of a region historically difficult to study. He hopes that having more data will shed light on the dynamics of Arctic Ocean freshening and acidification, which could affect of Arctic ecosystems and fisheries, and Arctic Ocean CO_2 uptake, which could affect the climate of our entire planet.

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

Human Composting Is a Greener Way to Go

Human composting might be a viable funeral option while also being more environmentally friendly than other methods of postdeath care, according to a recent pilot study.

"Currently, in the U.S. there are two primary options for disposal or final resting of the human body, which are cremation and burial," lead researcher Lynne Carpenter-Boggs said in a press conference.

"We are using fresh natural plant materials in addition to the human body and managing that through composting to produce high heat and rapid decomposition," she said. The resulting material "is multidecadal carbon storage and improves soil health and plant growth."

A Sustainable Alternative

In 2019, 93.8% of people who died in the United States were either buried or cremated, according to the National Funeral Directors Association. However, those two funeral methods each have a large environmental impact. Burial puts millions of liters of embalming fluid and thousands of cubic meters of wood into the ground. The carbon dioxide released into the atmosphere by cremation is equivalent to driving a car hundreds of kilometers.

More environmentally friendly funeral methods like alkaline hydrolysis and green burial are not widely available across the United States.

Composting deceased persons, or natural organic reduction, provides another sustainable alternative to cremation and burial. The concept got its start from the widespread practice of composting dead livestock.

"It's actually a fairly common practice on livestock farms," Carpenter-Boggs said. Carpenter-Boggs is a soil scientist at Washington State University in Pullman and a research adviser for the human composting company Recompose.

"Composting is an accepted practice and actually, in many areas, a promoted practice by departments of agriculture and departments of health for the disposal of livestock mortality." She said the team first composted livestock materials and then fine-tuned the processes for human remains.

"It's highly effective, but it's taken some thought and some redesign to make this a process that would be allowable and acceptable for human use," she added.

In the pilot study, the researchers composted six donated research subjects using natural plant material as a starter. After 4–7 weeks, each body turned 2–3 cubic yards of starter into 1.5–2 cubic yards of compost and bones. Carpenter-Boggs said that as with cremation, a commercial composting facility would likely processes the material further to deal with the skeletal remains.

The composting process heated the decomposing material enough to sterilize it to Environmental Protection Agency accepted levels, killing off most common bacteria and pathogens, Carpenter-Boggs said. That would make the resulting compost safe to keep in an urn or incorporate into the ground.

"We achieved proof of concept, and by our last set of subjects I was very happy with the end material," Carpenter-Boggs said. "For commercial use, there will be further changes in the infrastructure and process."

"It's highly effective, but it's taken some thought and some redesign to make this a process that would be allowable and acceptable for human use."

A Net Positive for the Environment

The total environmental impact of human composting can't be fully assessed before it becomes a commercial process, Carpenter-Boggs said, but it would likely not be entirely carbon neutral. Composting facilities would still need to be built, heated, and powered. However, unlike cremation and burial, composting would provide a net positive impact on the environment and sustainability.

Composting "is a fabulous option," Jennifer DeBruyn, a microbial ecologist at the University of Tennessee in Knoxville who was not involved with this work, told *Science News*. "The idea of applying it to humans, to me, as an ecologist and someone who has worked in composting, it just makes perfect sense, honestly."

Human composting has a long way to go before it becomes commonplace. In May 2019, Washington became the first state to legalize the practice. Similar legislation is under consideration in California and Colorado.

"There's tremendous interest in the method by the public and by funeral homes," Carpenter-Boggs said. "It will take time to legalize the process in more states and to standardize the process for new facilities."

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

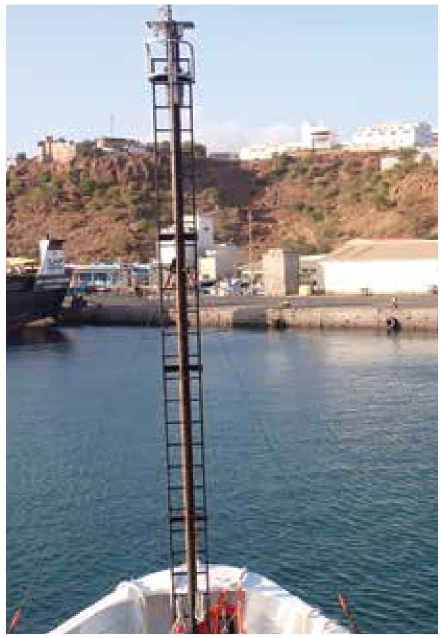
Trapped at Sea During a Pandemic Lockdown

Oceanographer Rainer Lohmann from the University of Rhode Island was on a research cruise near Barbados when the coronavirus spread rapidly into a pandemic.

"When we left, everything was normal," Lohmann said, speaking by phone while his ship, the R/V *Endeavor*, waited to dock in the city of Praia in Cape Verde on 17 March. "Now what we're hearing and seeing is that we're coming back to a country where we have to fight for toilet paper, where there are no hand sanitizers left, and you can't go out to restaurants."

The *Endeavor* left the Caribbean island of Barbados in late February and set off toward Cape Verde near West Africa, collecting sediment cores as it went. Lohmann and his team were investigating whether ocean sediments thousands of meters below the surface contained traces of atmospheric black carbon. After traversing much of the Atlantic Ocean, they had all the samples they needed and planned to fly home via Europe in mid-March.

But they faced a problem: The United States had just imposed strict travel restrictions through Europe. They needed a new way home.



The R/V Endeavor *sits in port in Cape Verde to receive supplies. To reduce the risk of infections, anyone who left the ship was not allowed back on board. Credit: Lydia Sgouros*

Plans Scrapped

Scientists around the world scrambled to adjust to a rapidly changing environment. Researchers have shuttered labs, switched to remote observing on telescopes, and learned to present their work virtually. A confirmed case of coronavirus disease 2019 (COVID-19) among the aircraft team of the Arctic expedition Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) quarantined about 20 of its members. Universities around the world have closed for the rest of the school year.

Research teams and oceangoing scientists who work in the field, often in remote locations, are facing new questions about how to conduct science safely. The organization that coordinates oceanographic research vessels across 59 academic institutions, University-National Oceanographic Laboratory System (UNOLS), resumed limited cruises again in May after quarantining crews.

Endeavor, one of the UNOLS fleet, is one of the few vessels that were midvoyage when the situation worsened. *Endeavor* barely made it to Cape Verde before its ports closed to ships, Lohmann said. Their flights through Europe blocked, he and five other scientists who live in the United States decided to stay on board the ship as it traveled back to its home port in Rhode Island. Two scientists on the cruise from Spain departed at Cape Verde to catch one of the few remaining flights back home.

"It's just one domino falling after the other, and you realize that you're just in the middle of this geopolitical crisis," Lohmann said.

And the Future Uncertain

UNOLS chair Craig Lee said that the group postponed cruises partly because it's not known how expeditions can mitigate the risks of transmission of COVID-19 while at sea. On 30 March, UNOLS provided a statement: "In the U.S. it is clear that the peak of the outbreak and any beginnings of a reduction or flattening of 'the curve' are still weeks away, and are based on successful social distancing efforts."

But on a ship, social isolation and physical distancing are "difficult to impossible," said Lee. Crew, technicians, and scientists may come from many locations for the same cruise, making it challenging to limit geographic risk. Putting a group in small quarters creates a higher risk of transmission, especially because testing participants for COVID-19 before the cruise isn't possible, according to Lee. While each cruise has at least one person trained in emergency medicine and significant medical supplies, ships have "far short of an ICU," said Lee, and it could take days to get to port.

Oceanographer Jonathan Fram at Oregon State University had a local cruise scheduled in late March to replace equipment in a long-term array installed off the coast. "We have a parking lot full of wonderful moorings, clean and ready to go," he said. Usually, the team services the array every 6 months to monitor, among other things, ocean acidification and low-oxygen conditions that can be harmful to marine life.

Their cruise was canceled, and Fram was concerned about their equipment left at sea. The moorings will "go dark" after a while, he said in March, and the autonomous, torpedo-shaped underwater vehicles (gliders) that traverse the array will have run out of batteries in May.

Pushing back the cruise means that the team missed recording data during the coastal ocean's transition from winter to spring, when ocean upwelling brings nutrient-rich waters along the Pacific Coast. "It's important to get a measure of that transition. And we're not going to be able to do that as well this year," Fram said.

As for the *Endeavor* on its international cruise, Lohmann said that the crew took precautions to limit any transmission risk while in port in Cape Verde. Food was handed over the raised platform connecting the ship to the dock, people did not leave the ship if they intended to get back on, and no new passengers joined for the voyage home. During their 2-week journey back, those on board took their temperatures daily and used disposable cutlery and dishware.

Lohmann said the expedition was laid over for 3 days in Barbados at the start of the cruise, meaning they missed the window to catch flights back to the United States. "We couldn't foresee that those 3 days were going to make the difference for most of us," Lohmann said.

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

Mountain Streams Exhale More Than Their Share of CO_2

Mountain streams, like this one in the Swiss Alps, emit more carbon dioxide than previously thought. Credit: hpgruesen

Sample a stream that runs through the Amazon, the Congo basin, or Canada's Northern Cordillera, and you're likely to measure a large amount of carbon dioxide (CO_2) dissolved in the water. That carbon comes mostly from plants, animals, and microbes that decompose in the water or return their carbon to the surrounding soil.

Mountain streams, however, start their journeys at high altitudes, which lack the carbon-rich soil of their lowland cousins. They haven't been widely studied, and the few measurements that exist suggest that their water is carbon poor. Because of that, it's been assumed that mountain streams don't contribute all that much to the combined CO_2 emission from river networks.

However, new research published in *Nature Communications* suggests that altogether, mountain streams likely emit more than half as much CO_2 as the oceans absorb annually and emit more CO_2 per square meter than tropical and boreal streams (bit.ly/mtn-stream-CO2).

"Mountain streams may represent 10%–30% of the total flux from streams and rivers. They represent just 5% of the surface area of streams and rivers," said lead researcher Åsa Horgby, a hydrogeologist at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. In terms of global carbon flux, "they are overrepresented, but it's really hard to estimate how much because we just don't have enough data."

"Mountain streams may represent 10%–30% of the total flux from streams and rivers. They represent just 5% of the surface area of streams and rivers."

Turbulence Releases Carbon Dioxide

Coauthor Tom Battin, who heads the Stream Biofilm and Ecosystem Research Laboratory at EPFL, said that their seeming unimportance to the carbon cycle and geographic inaccessibility have made mountain streams "aqua incognita" for carbon emission studies.

Recent research found that turbulent streams, like those flowing down mountainsides, exchange gas with the air more quickly than placid streams do, something that hadn't been accounted for in global models of rivers' CO_2 flux (bit.ly/stream-gas-exchange).

"If you have a higher concentration [of CO_2] in water than in the atmosphere, you have an outgoing flux. And then the opposite" for an ingoing flux, Horgby explained. "If you shake the water more, like if you have a Coca Cola bottle and you shake it, for example, you get a higher flux. And this is what's happening in mountain streams."

Prompted by that discovery, Horgby's team wanted to reevaluate mountain streams' contributions to the global carbon cycle. The researchers gathered CO_2 concentration and elevation measurements for mountain streams around the world to calculate the amount of CO_2 exchanged with the atmosphere.

"Our CO_2 model is building on 323 measurements, which is not a lot on a global scale," Horgby said, but in situ carbon data simply don't exist for most mountain streams. Too, mountain streams across the globe are very different from each other, so it wouldn't be accurate to use an average carbon flux measurement to represent unmeasured streams.

Instead, the researchers used the available data to develop new models that relate CO_2's rate of air exchange with more readily measured stream properties like temperature, width, and flow speed. Measurements from 12 high-altitude monitoring stations in the Swiss Alps validated those formulas, which the team then used to calculate the CO_2 flux one by one for more than 23,000 mountain streams in Switzerland and nearly 2 million across the globe.

"Rather than aggregating CO_2 and gas exchange for some area," said Robert Hall, a stream and river ecologist at the University of Montana's Flathead Lake Bio Station in Polson, "the authors predicted a CO_2 concentration and a gas exchange rate for each stream, multiplied these, and then summed them up by region. This approach should provide higher accuracy and allow estimation of uncertainty." Hall was not involved with this research.

An Ocean's Worth of Carbon

The researchers found that on average, a Swiss mountain stream emits 3.5 kilograms of carbon per year for every square meter of stream area. That flux per area is unexpectedly high, the team said. Even though mountain streams account for only roughly 5% of the global area covered by rivers and streams, their combined CO_2 outflux—about 1.7 gigatons of carbon per year—is about the same as that of tropical streams and "substantially higher" than that of boreal streams and rivers, which cover much more area.

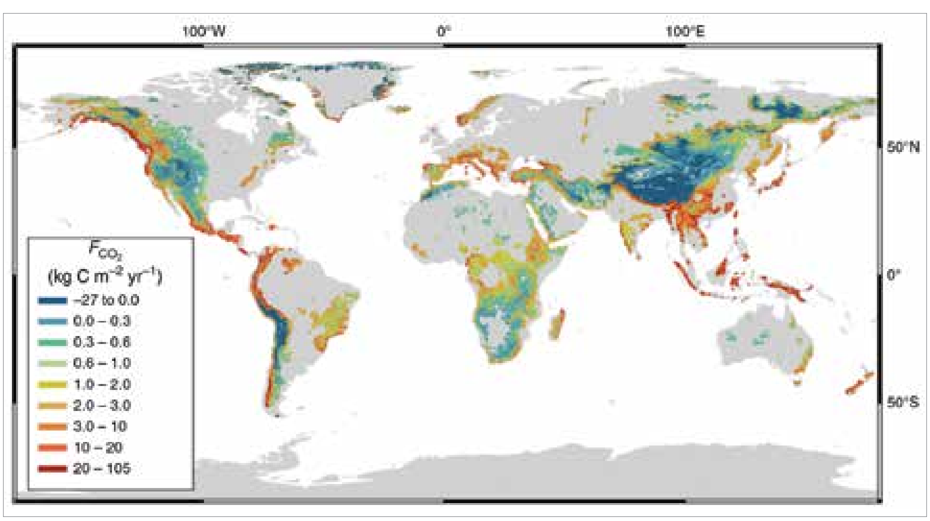
"When you take all of the inland waters—streams, rivers, lakes, etc.—we think that they emit as much CO_2 per year as the oceans globally absorb per year," Battin said. "The fluxes, although in different directions, are the same order of magnitude. For the ocean, it's something like 2.5 gigatons of carbon per year. For the inland waters it's between 2 and 3 gigatons."

Most of that emission has been assumed to come from rivers running through carbon-rich areas. This new estimate "implies that even in high-elevation ecosystems where terrestrial productivity may be low, there is a large transfer of carbon to aquatic systems," said David Butman. Butman studies the biogeochemistry of watersheds at the University of Washington in Seattle and was not involved with this research.

Churning water releases carbon dioxide up to 10 times more quickly than placid water. This is Furka Pass in Switzerland's Canton of Valais. Credit: Tambako The Jaguar, CC BY-ND 2.0 (bit.ly/ccbynd2-0)

The team found that by area, most mountain streams were net sources of CO_2. Just over 10%, however, were unexpected carbon sinks, including streams running through the interior of the Tibetan Plateau and the Altiplano region in the Andes. This study wasn't designed to find out why that might be, Horgby said, but will hopefully spark future research.

This study "presents a snapshot in time and space," Butman said. "This is our best guess at an annual contribution. However, we know that streamflow is driven by daily changes in precipitation, melting," and other factors. What's more, our understanding of gas exchange with turbulent water is still developing, Hall and Butman each pointed out, so these estimates of carbon flux may evolve along with our understanding of the underlying physical process. Battin said that data collection from the Swiss stations is ongoing and will help pin down the carbon flux more accurately.



Most of the world's mountain streams likely have a net annual outflux of carbon dioxide per area (light blue to red), but a few areas, like the Tibetan Plateau, are a net carbon dioxide sink (dark blue). The units in this map are kilograms of carbon per meter squared per year. Credit: Horgby et al., 2019, https://doi.org/10.1038/s41467-019-12905-z, CC-BY 4.0 (bit.ly/ccby4-0)

Where Does the Carbon Come From?

"High-mountain streams are typically above the tree line," Battin said, "so there's not much organic carbon up there. Their catchments are devoid of vegetation, and their soils are poorly developed."

So where does the carbon come from? The researchers suggested that the carbon might come primarily from the surrounding rocks and soil rather than from carbon dissolved directly into the stream water.

"These authors convincingly showed that the CO_2 from Swiss streams was some combination of soil respiration and weathering," Hall said. "Thus, the CO_2 was produced outside the stream and emitted to the atmosphere by the stream."

"Many of us claim," Battin said, "that streams and rivers and lakes emit lots of CO_2 into the atmosphere and therefore they are major players in the global carbon cycle. Now we understand more and more that especially for the high-mountain streams, most of that CO_2 is from the catchment, not from the stream itself."

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

Geodetic Data Pinpoint Earthquake-Prone Regions of the Himalayas

The Himalayas are home to 9 out of the 10 tallest mountain peaks on Earth. That mountain building is driven by plate tectonics, so it's no surprise that earthquakes frequently rock the region. Now, using precise GPS-derived velocities of the Indian and Eurasian plates, researchers have pinpointed four sections of the 2,000-kilometer-long Himalayan arc most likely to unleash destructive earthquakes. Historical records of ground shaking stretching back to the 16th century are largely consistent with these findings, the team showed.

Earthquakes in a Crumple Zone

Roughly 50 million years ago, the northward moving Indian plate began colliding with the southward moving Eurasian plate. This slow-motion collision and ensuing subduction of the Indian plate under the Eurasian plate created a crumple zone of mountains we now call the Himalayas.

But the Indian plate isn't diving cleanly under the Eurasian plate along the entire Himalayan arc—in some areas, the two plates are at a literal standstill, locked to one another and accumulating tectonic strain. When enough stress builds up, the plates will accelerate rapidly and slide past each other, which can produce a large earthquake.

"The Main Himalayan Thrust is the plate boundary fault where India is colliding with Eurasia, and many large, recent earthquakes, including the 2015 Gorkha earthquake in Nepal, occurred along that fault," said Marianne Karplus, a geophysicist at the University of Texas at El Paso not involved in the research.

To pinpoint which parts of the Himalayan arc are most at risk, Luca Dal Zilio, a geophysicist at the California Institute of Technology, and his colleagues investigated the degree of fault locking in the region. To do so, they compared the known convergence rate of the Indian and Eurasian plates (roughly 18 millimeters per year) with the plates' relative velocities derived from measurements from over 270 GPS stations.

"We can use these geodetic measurements to infer the degree of coupling," said Dal Zilio.

Creeping Along

Places where the plate convergence rate is about equal to the slippage of the Indian and Eurasian plates must have low levels of fault locking, the team concluded. They're creeping along, slowly releasing strain, so they aren't likely to unleash large earthquakes, Dal Zilio and his colleagues reasoned.

That conclusion is borne out by the earthquake record—the three sections of low fault locking the researchers found have been largely immune to intense ground shaking. "Around the regions where we have low coupling, we don't see—at least from historical data—any large events," said Dal Zilio.

These areas coincide with known subsurface ridges, which might consist of folded sections of rock or faults oriented transverse to the Main Himalayan Thrust, the researchers suggest. "They potentially represent a sort of barrier," said Dal Zilio, but more work needs to be done to better understand them. "We don't know much, honestly."

The 2015 Gorkha earthquake, which struck near Kathmandu, Nepal, killed thousands of people and damaged thousands of buildings, including this school. Credit: Owngchu1, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

A Coiled Spring

On the other hand, regions where the Indian and Eurasian plates aren't moving much relative to one another have high levels of fault locking, the scientists surmised. It's these areas that are cause for concern because they're storing up tectonic energy like a coiled spring. "That slip is accumulating over years and years," said Dal Zilio.

In their modeling, Dal Zilio and his collaborators found four segments of the Himalayan arc characterized by high levels of fault locking. These regions, typically hundreds of kilometers long, encompass parts of India, Nepal, and Bhutan. By estimating the amount of slip stored up in these segments, the team determined that earthquakes in excess of magnitude 8.5 were possible. That's supported by history: These regions are largely consistent with the lateral extensions of nine large (M_W = 7.5–8.7) temblors that occurred between 1505 and 2015, the team showed.

This work provides "a seismic hazard map of the Himalayan arc," said Dal Zilio. That's important because the region is home to millions of people, a sizable fraction of whom live in densely populated cities filled with earthquake-prone structures.

The team's results were published in *Geophysical Research Letters* (bit.ly/Main-Himalayan-Thrust).

This work contributes "important new models and ideas to the discussion of how the Main Himalayan Thrust geometry and seismogenic potential change across the Himalaya," said Karplus.

Dal Zilio and his colleagues are now using numerical models to better understand how earthquakes rupture near the Himalayan arc. Armed with data about fault geometry and subsurface geology, they're simulating cycles of large earthquakes to determine why some events are full ruptures, meaning that they nucleate from the bottom of the seismogenic zone and propagate all the way up to the surface.

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

Geohealth: Science's First Responders

Last December, the outbreak of coronavirus disease 2019 (COVID-19) started as a localized event but quickly spread globally because of lapses in surveillance and preparedness. In this sense, the current pandemic reflects many disasters—such as the oil well blowout on Deepwater Horizon and the aftermath of the 2011 Tohoku earthquake and tsunami—which typically begin as singular events of limited harm but through a cascade of human and systemic errors end up having catastrophic impacts.

This pandemic is not the first and likely won't be the last—Peter Daszak, an expert in disease ecology, has been warning us for years about zoonotic disease origination and the environmental pressures that cause viruses to leap into the human population. His contributions have greatly informed the discussion around how to stop the next severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2; the virus that causes the COVID-19 disease) from emerging from the forests and rampaging the globe.

Daszak is also one of the founding board members of AGU's journal *GeoHealth* (of which I am currently the editor in chief). Geoscientists have significant experience in disaster preparedness and disaster response, and a growing new community has been harnessing these skills in tandem with those of medical professionals, engineers, and social scientists to improve responses to events that have health, economic, and social impacts, including extreme events like pandemics.

An officer checks quality as police personnel make face masks and personal protective gear amid the COVID-19 outbreak in Jammu, India. Credit: Channi Anand/Associated Press

A Field that Bridges the Gap

The geohealth field emerged from the distinctive experiences of geoscientists who have collaborated broadly across disciplines to understand interactions between environmental processes and human health. Atmospheric chemist Mario Molina was part of the Nobel Prize–winning team that documented the links between chlorofluorocarbons (CFCs) and polar stratospheric ozone decline, leading to the Montreal Protocol and the international ban on CFCs. After accurately calculating the age of Earth from lead isotopes, geochemist Clair Patterson identified leaded gasoline as the main culprit of childhood lead poisoning and worked tirelessly and successfully to ban lead additives from fuel. Microbiologist Rita Colwell, the founding editor of *GeoHealth,* deconstructed the environment-disease interactions that drive cholera outbreaks and spearheaded low-cost local techniques to reduce cholera in drinking water. (Colwell was also the first woman to be named director of the U.S. National Science Foundation.)

The geohealth community aims to bridge gaps between geosciences and health sciences and define a role for itself in breaking the cycle of disasters made worse through preventable human missteps.

Protect Front Line Workers

One key geohealth lesson we've learned again and again from disasters is the necessity for protections and adequate supplies for first responders. The Deepwater Horizon oil spill in the Gulf of Mexico killed 11 workers on the drilling platform immediately and went on to cause a generation of harm to the environment and to human health. The first responders to the spill were exposed to high quantities of very reactive and dangerous fresh hydrocarbons (these become somewhat more benign as they mature in the marine environment). A lack of adequate personal protective equipment (PPE) on-site combined with poor understanding of those health risks and the urgency of mitigating the disaster led to severe skin and breathing exposures for many first responders, along with illnesses that persisted for years.

The failure to learn from and implement changes based on this lesson is a tough one to see playing out again now with the shortages of testing kits, medical supplies, and PPE to help slow the spread of COVID-19. Similar to the Deepwater hydrocarbons, the virulence of SARS-CoV-2 was poorly understood at the outset of the pandemic, leading to early infections in health workers. No matter our level of understanding, first responders are always at higher risk of exposures to environmental hazards and viral pathogens. A recent report by Colwell and human ecologist Gary Machlis for the American Academy of Arts and Sciences noted the critical importance of involving scientists along with health professionals in crisis training exercises that would, ideally, make sure risk data are included in the creation of disaster plans (bit.ly/crisis-science).

The outcomes from the Deepwater Horizon disaster would have been markedly different if knowledge of the dangers of fresh hydrocarbons had bolstered PPE use and ensured that redundant mitigation equipment had been present. Similarly, if governments outside of China had involved scientists in national planning from the start, they would have been more aware of the potential for logarithmic growth in disease spread and thus of the need to produce and stockpile PPE for first responders, even if better quarantine procedures from the start meant they would not ultimately be needed.

Worst-Case Scenario Warning Systems

Another lesson the geohealth community stresses is the need for adequate and accurate warning systems. For example, Japan has in place some of the most advanced construction standards for mitigating earthquake shaking, as well as widespread early-warning systems. Then the *M*9.1 earthquake centered at Tohoku shook the region in 2011. The earthquake early-warning system functioned well, but the safe zones and seawalls were designed and built to handle only inundations from tsunamis consistent with typical earthquakes in the region, not for a worst-case-scenario event. Yet the 2011 tsunami was massive, with waves ranging from 10 to 40 meters high approaching at speeds of up to 700 kilometers per hour. The protective systems failed, and tens of thousands of people died. Scientists now know that an event like this is consistent with the paleorecord of tsunamic deposits in the region and could have been predicted and planned for (bit.ly/geohealth-tsunami).

The Tohoku event, along with the 2004 earthquake and tsunami at Sumatra, Indonesia, helped to catalyze the geohealth community to develop better early-warning systems for seismic hazards as well as tsunamis. These tools capitalize on mobile technologies to give real-time warnings, thus saving lives.

In the context of COVID-19, early warning means having test kits available. The logarithmic growth prediction coupled with rapid vector transport via air travel should have led to massive production and distribution of tests so that we could pinpoint and isolate emerging hot spots. The assumption that the spread of this disease would fizzle before becoming globally widespread, as the SARS outbreak did in 2003–2004, is akin to that about the size of potential tsunami events prior to Tohoku—and it's an assumption that has resulted in the pandemic we see today.

Finally, risk messaging has to be sound and consistent throughout a disaster. As geohealth experts have recognized from the Deepwater Horizon and Tohoku events, stress and anxiety during disasters drive a host of short- and long-term pathologies that extend to physical health. The key to mitigating these effects is to analyze the progress of a disaster using sound science and provide science-informed recommendations to citizens so that they are—and feel—prepared.

Give Clear, Science-Based Messaging to the Public

When the Tohoku tsunami led to the meltdown of several reactor cores at the Fukushima Daiichi Nuclear Power Plant, the messaging about health impacts of the resulting radiation hazards was inconsistent, inaccurate, and purposefully optimistic. The immediate monitoring performed to assess the amount and distribution dynamics of radiation released, which are influenced by topography and atmospheric circulation, was not nearly sufficient. And the regulatory agencies responsible for the assessments simply drew concentric

The geohealth community is already mobilizing to understand COVID-19 dynamics and its secondary impact on health and environment.

circles around the release site representing varying risk levels. It was not until a loose coalition of citizen scientists took up the task that there was any documentation of the highly variable radiation distribution across the region. Meanwhile, the regulatory agencies first downplayed the risks, then provided inconsistent enforcement of no-travel radiation zones that were not science based and that changed daily.

Research on the societal stress this poor messaging caused has led to new approaches to engaging communities in risk messaging. We should be executing what we've learned from these lessons today. We know enough about viral dynamics and pandemic spread to accurately and consistently inform the public about infection avoidance and risk. Using the geohealth community's approach to messaging would help relieve public anxiety while still containing the outbreak.

From events like the Deepwater Horizon spill and the Tohoku tsunami, the geohealth community has learned to better plan for and respond to disasters and to better inform communities, cities, and governments about best practices. Our community is already mobilizing to understand COVID-19 dynamics and its secondary impact on health and environment. Geohealth researchers are dedicated to documenting links between infectious disease, climate, human migration, risk communication, and system responses—lessons learned from making these links can help efforts to handle early stages of a disaster and keep it from growing. Even amid a pandemic, it's not too late to start adopting these lessons and, we hope, to avoid a next time.

By **Gabriel Filippelli** (gfilippe@iu.edu), Center for Urban Health, Indiana University–Purdue University Indianapolis; Editor in Chief, GeoHealth

▶ Read the article at bit.ly/Eos-geohealth

The United States Needs Sustainable River Policy Now

Australia's third-longest river, the Darling, normally experiences periods of medium to low flow punctuated by flood events. But vast stretches of the river in New South Wales have been bone dry for the past two summers, and in 2019 the river was dry by early spring.

The lack of flows has left communities along its banks in dire straits, with many trucking in water to meet even basic domestic water requirements. Millions of dollars have been spent building pipelines to distant reservoirs, while groundwater resources have also been put under increased stress to fill gaps. River ecosystems have also felt the impacts acutely, with mass fish deaths being just one example.

Periods of drought are partly responsible for the diminishing flows in the Darling. More important, however, are increasing water withdrawals over several decades that have taken a toll on this river, whose flow has been heavily altered by damming and diversion for irrigation.

The challenges posed by the increasing frequency and duration of no-flow periods in rivers are not unique to arid regions: Over half of the world's streams and rivers are dry for some part of the year, and the geographic extent of nonperennial waterways is forecast to increase because of climate change and increasing water use. Headwaters in humid regions typically also dry out for part of the year because they drain such small regions. These streams, too, are being affected by climate change.

Altered patterns of drying and flow create hardships in societies (and ecosystems) that use nonperennial waterways for drinking water, irrigation, and other services. Water policies can thus have substantial repercussions for the management of waterways, potentially irreversibly damaging the freshwater ecosystems needed to support human well-being.

Despite scientists' clear calls for enhanced legislative protection of the flows and ecosystems of nonperennial rivers and substantial research efforts to understand and communicate the ecological implications of drastic variations in flow, legal protections of these waterways have actually decreased in recent years in many places. As a case in point, in the United States a 2015 update of the Waters of the United States (WOTUS) rule would have qualified both perennial and nonperennial waterways for water quality protections, but implementation of this update was halted in 2019 (and a new regulation further scaling back the definition of WOTUS was signed in January).

The dry Rio Puerco, near the Sevilleta Long Term Ecological Research site about 80 kilometers south of Albuquerque, N.M., is seen here in September 2019 during a field trip to the U.S. Geological Survey's Rio Puerco stream gauge organized as part of a Dry Rivers Research Coordination Network workshop. Credit: Margaret Shanafield

How can scientists and others turn this trend around and help accelerate the adoption of science-based legal protections for nonperennial rivers? At a recent workshop of the Dry Rivers Research Coordination Network, hydrologists, ecologists, and biogeochemists identified three crucial areas to act upon to protect and restore nonperennial rivers. These include identifying key knowledge gaps to create science-based solutions; developing a common language defining nonperennial river systems; and collaborating with social scientists, water managers, and policy makers to facilitate the translation of knowledge into policy action.

Filling Data Gaps for Nonperennial Rivers

Our understanding of how nonperennial rivers function is still largely in its infancy. Over the past 2 decades, scientific interest in this field has widened considerably, resulting in conceptual advances, such as in improved understanding of streamflow generation mechanisms, the importance of streamflow periodicity to ecological communities, and the characteristics of certain flow regimes (patterns of flow over time and space). These advances have not only improved scientific models but also highlighted where data gaps hamper improvements in science-supported policy.

One thing is clear: Sufficient data are vital for understanding river networks and human impacts on them. River flow measurements are the most crucial type of data; science-based solutions to respond to effects of global climate change and to altered hydrologic and ecological conditions in river systems will be realized only if flows in all types of waterways are represented. Long-term data on nonperennial rivers in particular are critical for supporting hydrometric networks that guide the allocation of resources to support human and ecosystem water needs and for forecasting drought risk to societies.

Yet globally, gauges on perennial river systems far outnumber those on nonperennial rivers. This is largely because stream gauges

Researchers with the Dry Rivers Research Coordination Network and other multidisciplinary research groups are piecing together the science of nonperennial rivers. Credit: Margaret Shanafield

were installed for flood protection or to ensure reliable water supplies. There are some exceptions, though. In Australia, where 70% of the country's rivers are nonperennial, the gauge network includes high-quality measurements of flow in nonperennial streams and rivers.

Although we know that nonperennial rivers are naturally common over large areas of several continents, we still lack information about the climatic and human drivers of no-flow periods. Our current understanding of aquatic ecosystems is based mainly on research in perennial streams and may not reflect patterns and processes relevant to the management of intermittent waters. Only with a strong foundation in interdisciplinary, data-driven science can nonperennial waterway policies effectively manage these rivers' important flow regimes—providing water to both people and the aquatic environment when it's most needed—as well as aquatic wildlife, biogeochemical reactions (e.g., a river's ability to clean itself), and important cultural and archaeological features along the rivers' corridors.

Common Language, Collective Action

Over the past 20 years, scientists have drawn attention to strong cultural and societal links to local nonperennial waters, including, for example, their prominence in Aboriginal Dreamtime stories in Australia, their historical use as cultural and transportation highways, and their value for recreation and reconnecting with the outdoor world. To encourage protection of these resources at national levels, we require a common, accepted terminology. Language shapes public and political discourse. Only with shared language can we begin to evaluate human-induced deviations from natural flow regimes and efforts to ameliorate the consequences. Yet we still lack a common definition of nonperennial rivers. Is an intermittent river the same as one that is seasonal or temporary or ephemeral?

Early efforts to rally the scientific community around a set of definitions and a common terminology were not successful, so the confusion among definitions continues. Without agreement on terminology, science-based policy decisions can lead to legal challenges and public confusion. And unclear definitions of terms like intermittent and ephemeral may give rise to ambiguity in the purview of legal protections offered. For example, the proposed 2015 update of WOTUS attempted to legislate differently for intermittent versus ephemeral waterways. For this kind of policy to be scientifically based, though, scientists must first agree on what these terms mean.

We need a renewed, global effort to better understand and classify nonperennial waterways within a global terminology.

Other changes to terminology are under consideration in legislation around the world. Therefore, we need a renewed, global effort to better understand and classify nonperennial waterways within a global terminology. We expect that this shared language will be based on commonalities and differences in hydrological, ecological, and biogeochemical functioning of waterways and will improve understanding and communication across systems and disciplines.

Interdisciplinarity Beyond the Natural Sciences

There is a growing movement toward interdisciplinary research on nonperennial streams, in which different types of scientists work together to bridge conceptual and knowledge gaps related to these systems. Multiple collaborative, interdisciplinary groups focused on understanding and protecting nonperennial rivers have coalesced in recent years, resulting in considerable successes.

The 1000 Intermittent Rivers Project, for example, brings together ecologists, biogeochemists, and hydrologists from around the world to understand the biodiversity of nonperennial rivers and streams; this group has already shown how nonperennial rivers contribute to the global carbon cycle. Similarly, the European Science and Management of Intermittent Rivers and Ephemeral Streams project gathered a diverse team of more than 350 scientists from 31 European Union (EU) countries to compile and analyze available EU data sets on nonperennial waterways and improve their management within the EU Water Framework Directive. These projects were initiated by an international, multidisciplinary team of 12 nonperennial stream experts from the United States, the European Union, and Australasia, which developed the first international database on nonperennial streams.

In the United States, the National Science Foundation–funded Dry Rivers Research Coordination Network has assembled scientists spanning disciplines and from three continents to identify overarching scientific knowledge gaps and to develop conceptual models that merge multiple data sets to promote the future sustainability of nonperennial streams.

Yet acceptance and adoption of scientific understanding will require changes in the public mindset and changes in water management regulations. It also will require dialogue among natural scientists, social scientists, policy makers, and water managers. Only by bringing natural and social scientists together can we change, for example, the misconceptions, documented in Europe and the United States, that the only valuable river is one that is flowing and that nonperennial rivers are simply drainage ditches for removing unwanted stormwater. Scientists have begun this effort by improving visualizations of the water cycle and engaging directly with citizen scientists, but more work is needed.

Only by bringing natural and social scientists together can we change the misconception that the only valuable river is one that is flowing.

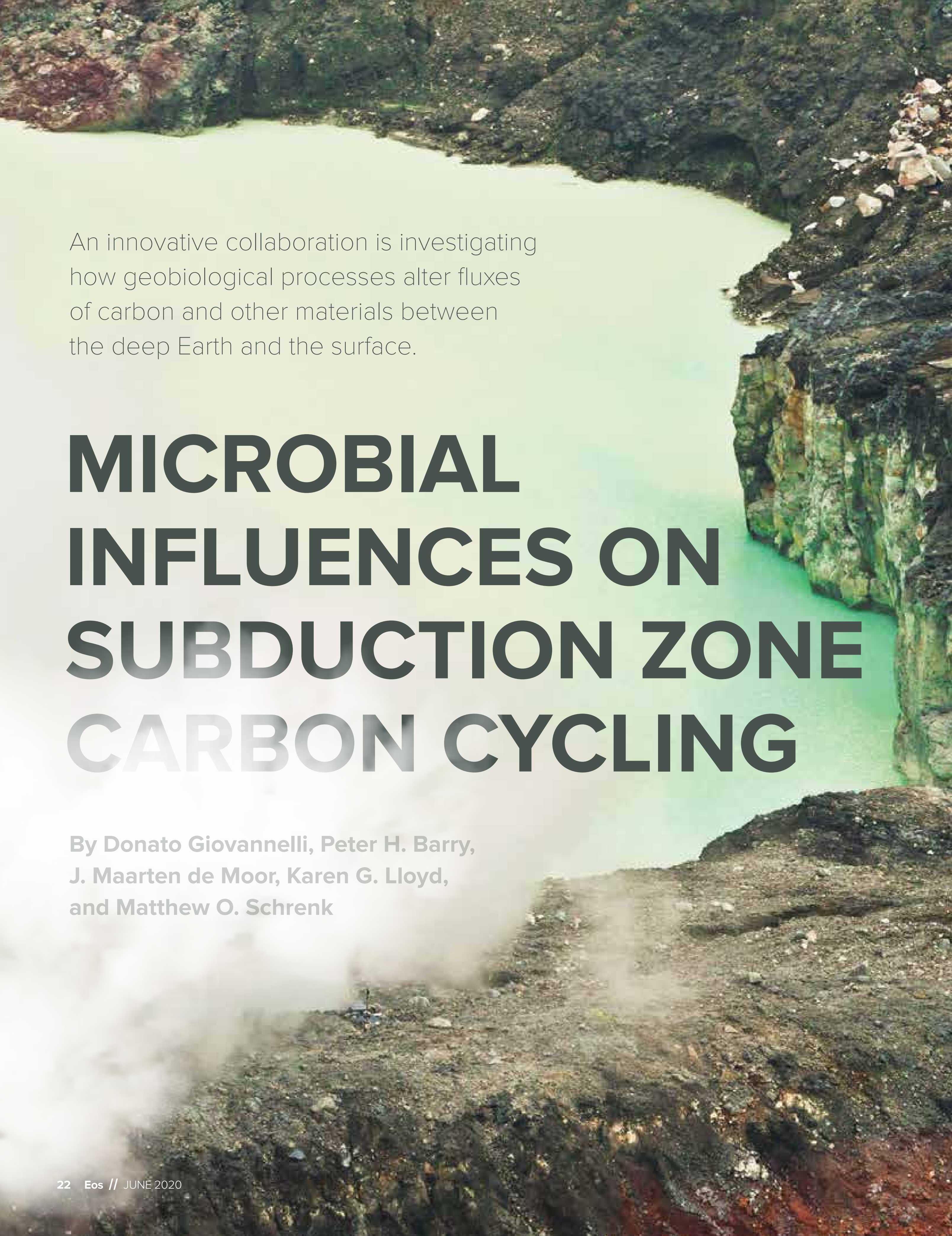
Another reason more dialogue among these groups is needed is the increasing frequency and severity of drought in more temperate regions, which are altering the extent of protection needed to keep these systems healthy at a far faster pace than that at which policy typically functions. This is apparent even in Australia, where the value of nonperennial rivers is broadly accepted yet widespread ecological degradation of river systems continues.

Policy makers and the public must start placing the sustainability of river ecosystems first, so that the rivers can continue to sustain us in the long term. To achieve this change in mindset, scientists must effectively partner with members of these groups to promote broad uptake of scientific understanding in public discourse and in science-based regulations for the improved health of river systems. We call for the formation of a global, collaborative network led by the scientific community and intended to foster emerging interdisciplinary links among scientists and to accelerate such promotional efforts.

Acknowledgments
The Dry Rivers Research Coordination Network, of which the authors are part, is supported by funding from the U.S. National Science Foundation (DEB-1754389).

By **Margaret Shanafield** (margaret.shanafield@flinders.edu.au), Flinders University, Adelaide, S.A., Australia; **Sarah Godsey,** Idaho State University, Pocatello; **Thibault Datry,** French National Institute for Agriculture, Food and Environment (INRAE), Villeurbanne, France; **Rebecca Hale,** Idaho State University, Pocatello; **Samuel C. Zipper,** Kansas Geological Survey, University of Kansas, Lawrence; **Katie Costigan,** University of Louisiana at Lafayette; **Corey A. Krabbenhoft,** University at Buffalo, Buffalo, N.Y.; **Walter K. Dodds,** Kansas State University, Manhattan; **Margaret Zimmer,** University of California, Santa Cruz; **Daniel C. Allen,** University of Oklahoma, Norman; **Michael Bogan,** University of Arizona, Tucson; **Kendra E. Kaiser,** Boise State University, Idaho; **Ryan M. Burrows,** Australian Rivers Institute, Griffith University, Brisbane, Queensl.; **John C. Hammond,** Maryland–Delaware–D.C. Science Center, U.S. Geological Survey, Baltimore, Md.; **Michelle Busch,** University of Oklahoma, Norman; **Stephanie Kampf,** Colorado State University, Fort Collins; **Meryl C. Mims,** Virginia Polytechnic and State University, Blacksburg; **Amy Burgin,** Kansas Biological Survey, University of Kansas, Lawrence; and **Julian D. Olden,** University of Washington, Seattle

▶ **Read the article at bit.ly/Eos-dry-rivers**



An innovative collaboration is investigating how geobiological processes alter fluxes of carbon and other materials between the deep Earth and the surface.

MICROBIAL INFLUENCES ON SUBDUCTION ZONE CARBON CYCLING

By Donato Giovannelli, Peter H. Barry, J. Maarten de Moor, Karen G. Lloyd, and Matthew O. Schrenk


The hyperacidic Laguna Caliente sits in a crater near the summit of Poás volcano in Costa Rica.
Credit: Max Dominik Daiber/Alamy Stock Photo

In subduction zones, where one tectonic plate sinks below another into our planet's mantle, carbon, water, and other volatile species like hydrogen and sulfur move between the surface and the deep Earth. Scientists quantify this cycling of elements by estimating how much of each is subducted with downgoing slabs and how much is emitted by volcanic arcs, the chains of volcanoes that form on the upper plate overlying a subducting plate. Taking stock of carbon cycling is especially important, because the process influences the amount of carbon dioxide in the atmosphere and, ultimately, the long-term stability of Earth's climate.

Our current understanding of subduction, from a geochemical perspective, largely neglects the role of biology in the upper plate.

Previous research has constrained such carbon fluxes from volcanic-arc regions around the world, including in Central America [e.g., *de Moor et al.,* 2017]. But fluxes in fore arcs and back arcs—the areas on either side of volcanic arcs—remain poorly understood [*Füri et al.,* 2010], and carbon in these areas may be modified by or consumed by such secondary processes as mineral precipitation or microbial activity near the surface [*Venturi et al.*, 2017]. Recent studies have also highlighted the importance of an extensive global subsurface microbial biosphere, which may play significant roles in altering Earth's biogeochemical cycles [*Magnabosco et al.,* 2018].

Microbial sulfide oxidizer filaments in the stream of Quepos hot spring in the forearc of the Costa Rica convergent margin. Microbes use carbon derived from the subducted slab as their energy source. Credit Peter Barry/BMS

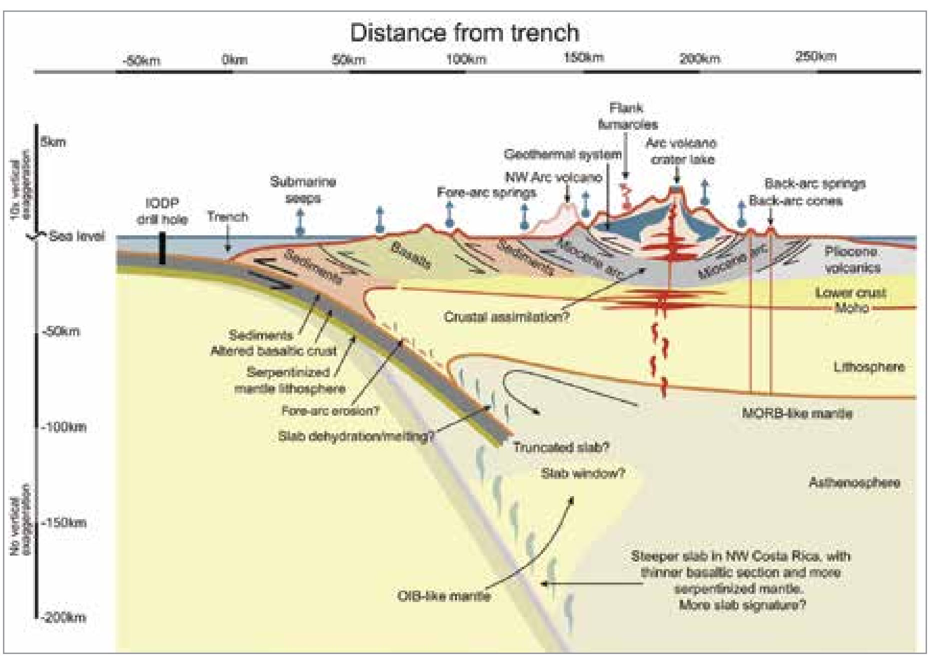


Fig. 1. This cross section of the Costa Rica subduction zone shows, among other features, the subducting Cocos plate (dark gray) with volatile fluids rising from it, as well as the fore-arc, volcanic-arc, and back-arc regions. During field campaigns in 2017 and 2018, researchers sampled 50 geothermal sites across the fore-arc and volcanic-arc regions. Abbreviations are IODP, International Ocean Discovery Program; MORB, mid-ocean ridge basalt; and OIB, ocean island basalt.

Our current understanding of subduction, from a geochemical perspective, largely neglects the role of biology in the upper plate. This is partly because of disciplinary boundaries that often confine researchers to their specific fields of expertise. To improve our understanding of subduction and the fate of carbon in a holistic way, an international group of early-career scientists launched a research initiative in 2016 that brought together a large multidisciplinary team to study the Costa Rica convergent margin (Figure 1). Funded by the Alfred P. Sloan Foundation and under the umbrella of the Deep Carbon Observatory, the Biology Meets Subduction project is a novel scientific effort to improve understanding of the intimate relationships between the geosphere and the biosphere at a convergent margin.

Costa Rica Field Campaigns

The Biology Meets Subduction project seeks to answer four scientific questions: What is the influence of biological activity on carbon outgassing at the Costa Rica convergent margin? Can biological signatures be traced through subduction processes and distinguished from surface biological activity by using isotopic data? By using this information, can we better constrain carbon sources and fluxes? And can we improve deep-carbon budget estimates for the Costa Rica convergent margin?

In addressing these specific questions, the project, which is in the data analysis stage, has the potential to improve global carbon flux estimates by describing a major and previously overlooked role of the deep microbial biosphere in geological processes.

Researchers sampled the lake inside Poás volcano in Costa Rica during a field campaign in February 2017. The lake has a pH of less than 1, yet microbes thrive there by feeding off volcanic sulfur compounds. Credit: Donato Giovannelli/Biology Meets Subduction

The Costa Rica convergent margin has a large, well-studied fore arc that is subaerial, presenting the opportunity to track volatiles like carbon across this important part of the margin. In February 2017 and April 2018, a team of researchers from six nations convened in Central America to conduct two field expeditions across and along the volcanic arc in Costa Rica and Panama. Members of each of the four Deep Carbon Observatory science communities (Deep Energy, Deep Life, Reservoirs and Fluxes, and Extreme Physics and Chemistry) participated.

In total, the team sampled 50 geothermal sites across the region, gathering hundreds of individual samples of gases, fluids, sediments, and rocks. To link biogeochemical processes, the team collected samples from hydrothermal springs with a wide range of both temperature (23°C–89°C) and pH (0.8–10.8) that were simultaneously analyzed for gas geochemistry, aqueous chemistry, mineralogy, and microbiology. The researchers tracked and distinguished surface-derived carbon (arising from processes like photosynthesis) from deeply sourced carbon by analyzing the isotopic compositions of different carbon pools (such as dissolved inorganic carbon, dissolved organic carbon, gaseous carbon dioxide, and total organic carbon) as well as by analyzing helium isotope data.

A carbon dioxide (CO_2)– and iron-rich artesian well in the backarc of the Costa Rica convergent margin. Large amounts of CO_2 are released from low temperature springs throughout the backarc. Credit Donato Giovannelli/BMS

A Subsurface Sink

Early results from the expeditions revealed a previously unrecognized sink for volatiles in the fore arc of the Costa Rica margin [*Barry et al.,* 2019a, 2019b]. Carbon isotope compositions of deep hydrothermal waters rising toward the surface showed a clear Rayleigh distillation (the selective partitioning of isotopes between two reservoirs as material moves between them) resulting from calcite precipitation in the fore arc. This precipitation accounts for the removal of 91% of the inorganic carbon in these fluids that are rising from the top of the subducting slab. An additional 3% of this inorganic carbon, in the form of outgassing carbon dioxide, was sequestered as biomass by chemolithoautotrophic microbes (i.e., microbes that produce biomass from carbon dioxide in the absence of light), which might also actively mediate calcite deposition [*Aloisi et al.,* 2006]. Calcite and microbial biomass therefore act as subsurface filters for fore-arc carbon, altering the fluxes that would otherwise be released directly to the atmosphere.

The Costa Rica convergent margin has a large, well-studied fore arc that is subaerial, presenting the opportunity to track volatiles like carbon.

By using the data collected during the 2017 expedition, *Barry et al.* [2019a] also calculated that as much as about 19% less carbon is transported into the mantle with subducting plates than was thought from previous estimates. This has significant implications for the accuracy of global carbon models, which might overestimate carbon exportation to the deep Earth, and for our understanding of Earth's past climate and reduction-oxidation conditions. For example, the authors suggested that fore-arc carbon sinks that are similar to the one identi-

Karen Lloyd and Donato Giovannelli sample fumarolic encrustations in the degassing crater of Poás volcano. Credit Marcus Lehmann/BMS

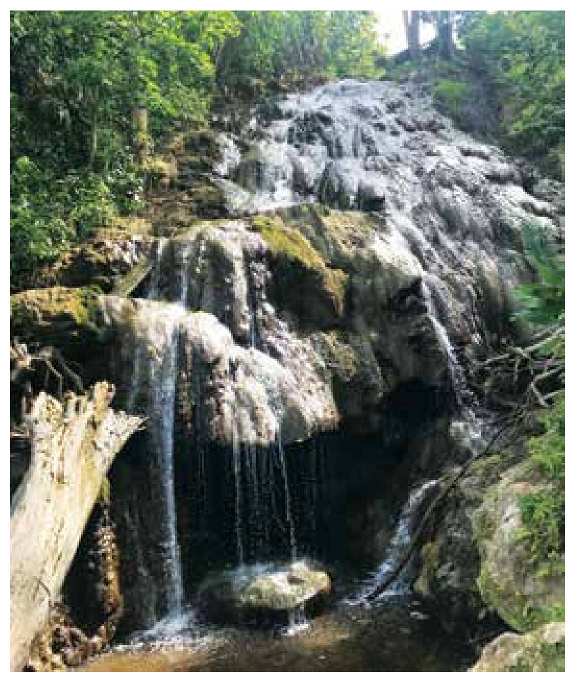
fied in the Costa Rica margin might have contributed to the accumulation of oxygen during the late Archean and early Proterozoic (roughly 3 billion to 2 billion years ago) and should thus be considered when modeling the effects of subduction zones on carbon cycling through deep time.

> This project represents a unique opportunity to link the effect of biology to large-scale geological processes and will help clarify the role of biology in influencing volatile cycling at convergent margins.

Linking Geology and Biology

The Biology Meets Subduction team is currently analyzing the microbial functional diversity and the taxonomic diversity of the samples collected (K. M. Fullerton et al., Plate tectonics drive deep biosphere microbial community composition, EarthArXiv, bit.ly/tectonics-microbes). Results of this work will provide insights into connections between microbial metabolism and volatile cycling in the Costa Rica margin, as well as insights into links between tectonic processes and microbial community compositions and functions.

This information will help explain microbial connections to deep-subsurface processes, a topic that has recently been explored in hot springs elsewhere in the world, including in Yellowstone National Park and in the Taupō Volcanic Zone in New Zealand [*Colman et al.*, 2019; *Power et al.*, 2018]. Overall, this project represents a unique opportunity to link the effect of biology to large-scale geological processes and will help clarify the role of biology in influencing volatile cycling at convergent margins.



A large carbonate mound located near a hot spring in the backarc. Calcite precipitation appears to be a pervasive carbon sink. Credit Peter Barry/BMS

The early results from the project raise questions about the role of secondary processes acting to sequester carbon and volatiles in other tectonic environments, like back-arc regions, continental rifts, and fold and thrust belts. Investigating these environments opens interest-

Drone view of Poás fumarole field. The lake, located in the center of the crater, is formed by meteoric waters that interact with magmatic gases. It is extremely dynamic and disappears during periods of more intense heat flow and volcanic activity. Credit Peter Barry/BMS

ing opportunities to further study the complex interplay between the geosphere and the biosphere that has maintained our planet's habitability for billions of years.

Acknowledgments

We thank the many collaborators on this project and all the team members who took part in the field campaigns. The Biology Meets Subduction project was funded by the Alfred P. Sloan Foundation and the Deep Carbon Observatory (grant G-2016-7206).

References

Aloisi, G., et al. (2006), Nucleation of calcium carbonate on bacterial nanoglobules, *Geology, 34*(12), 1,017–1,020, https://doi.org/10.1130/G22986A.1.

Barry, P. H., et al. (2019a), Forearc carbon sink reduces long-term volatile recycling into the mantle, *Nature, 568*(7753), 487–492, https://doi.org/10.1038/s41586-019-1131-5.

Barry, P. H., et al. (2019b), Helium, inorganic and organic carbon isotopes of fluids and gases across the Costa Rica convergent margin, *Sci. Data, 6,* 284, https://doi.org/10.1038/s41597-019-0302-4.

Colman, D. R., M. R. Lindsay, and E. S. Boyd (2019), Mixing of meteoric and geothermal fluids supports hyperdiverse chemosynthetic hydrothermal communities, *Nat. Commun., 10*(1), 681, https://doi.org/10.1038/s41467-019-08499-1.

de Moor, J. M., et al. (2017), A new sulfur and carbon degassing inventory for the Southern Central American Volcanic Arc: The importance of accurate time-series data sets and possible tectonic processes responsible for temporal variations in arc-scale volatile emissions, *Geochem. Geophys. Geosyst., 18*(12), 4,437–4,468, https://doi.org/10.1002/2017GC007141.

Füri, E., et al. (2010), Carbon release from submarine seeps at the Costa Rica fore arc: Implications for the volatile cycle at the Central America convergent margin, *Geochem. Geophys. Geosyst., 11*(4), Q04S21, https://doi.org/10.1029/2009GC002810.

Magnabosco, C., et al. (2018), The biomass and biodiversity of the continental subsurface, *Nat. Geosci., 11*(10), 707–717, https://doi.org/10.1038/s41561-018-0221-6.

Power, J. F., et al. (2018), Microbial biogeography of 925 geothermal springs in New Zealand, *Nat. Commun., 9*(1), 2876, https://doi.org/10.1038/s41467-018-05020-y.

Venturi, S., et al. (2017), Fractionation processes affecting the stable carbon isotope signature of thermal waters from hydrothermal/volcanic systems: The examples of Campi Flegrei and Vulcano Island (southern Italy), *J. Volcanol. Geotherm. Res., 345,* 46–57, https://doi.org/10.1016/j.jvolgeores.2017.08.001.

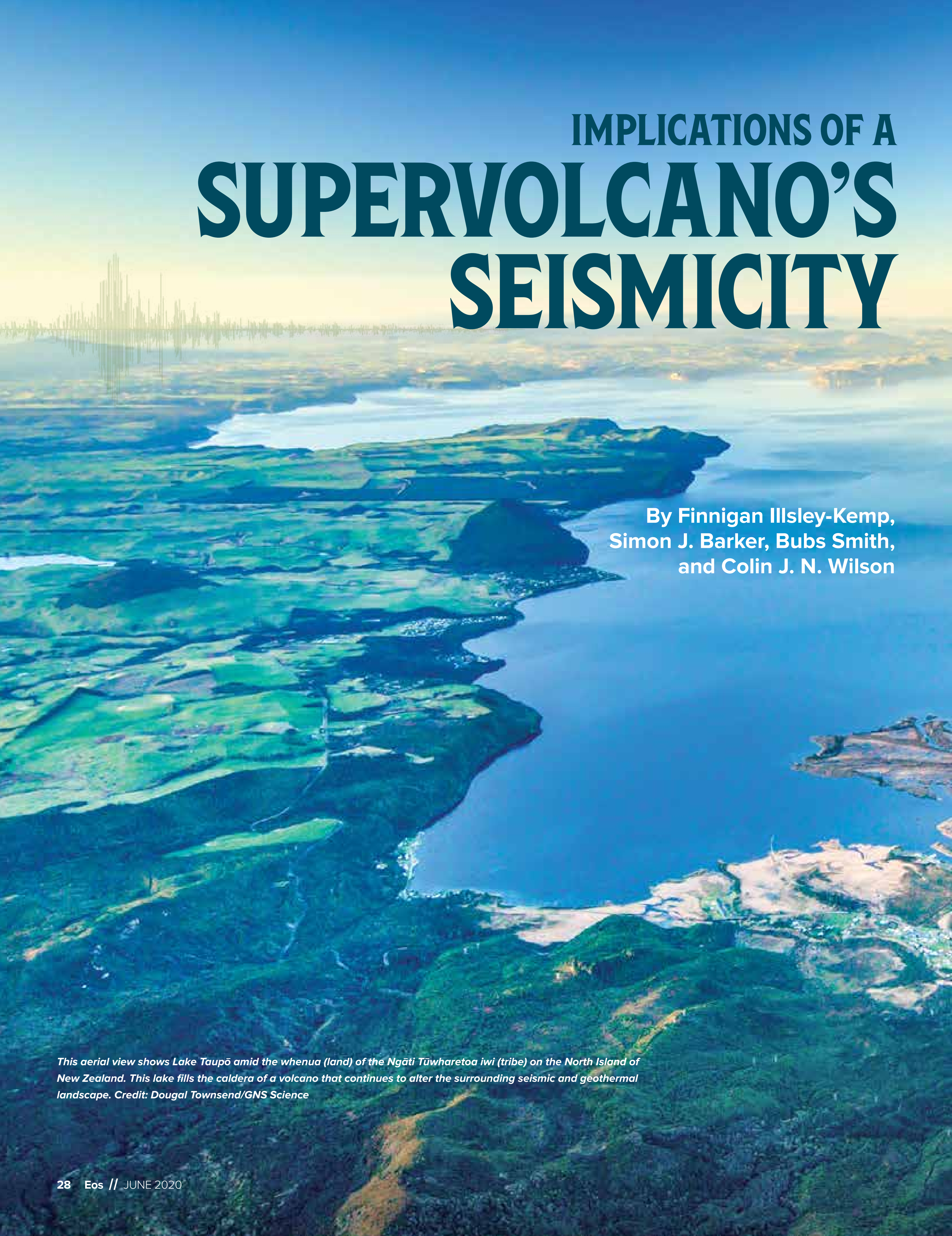
Author Information

Donato Giovannelli (donato.giovannelli@unina.it), Department of Biology, University of Naples Federico II, Naples, Italy; **Peter H. Barry,** Woods Hole Oceanographic Institution, Woods Hole, Mass.; **J. Maarten de Moor,** Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI), Universidad Nacional de Costa Rica, Heredia; also at University of New Mexico, Albuquerque; **Karen G. Lloyd,** University of Tennessee, Knoxville; and **Matthew O. Schrenk,** Michigan State University, East Lansing

▶ Read the article at bit.ly/Eos-subduction-zone-carbon

IMPLICATIONS OF A SUPERVOLCANO'S SEISMICITY

By Finnigan Illsley-Kemp, Simon J. Barker, Bubs Smith, and Colin J. N. Wilson



This aerial view shows Lake Taupō amid the whenua (land) of the Ngāti Tūwharetoa iwi (tribe) on the North Island of New Zealand. This lake fills the caldera of a volcano that continues to alter the surrounding seismic and geothermal landscape. Credit: Dougal Townsend/GNS Science

Last year's rumblings beneath New Zealand's Taupō supervolcano, the site of Earth's most recent supereruption, lend new urgency to research and outreach efforts in the region.

Opposite Page: XXXXXX; This Page: Top Right: XXXX

The deadly 9 December 2019 eruption at Whakaari (White Island) in New Zealand's Bay of Plenty reminded the world of the variety of volcanoes in New Zealand capable of causing major impacts on modern society. However, the magnitude of this event was very small in comparison with other eruptions in the area's geological past. Twenty-five millennia ago, another volcano in what is now New Zealand blasted a volume of ash and pumice into the air large enough to have covered all of California with 2.8 meters of debris. Since then, no other volcano on Earth has ejected more material.

Today that volcano is known as Taupō, and it sits at one of the geographic and cultural focal points of New Zealand's North Island (Figure 1). The odds of another such supereruption (an eruption that ejects at least 1,000 cubic kilometers of material) occurring at Taupō in the near future are effectively zero. But lower-magnitude eruptions have occurred there since, and the rumbling and shifting that continue under Taupō today are a source of ongoing concern and uncertainty about whether a hazardous blast could be on the horizon. Last year, Taupō was unusually seismically active, but scientists don't know whether that activity represents just "business as usual" (volcanoes often show signs of stirring without any eruption).

Any eruption today would have serious effects for people in the region, spreading ash and debris across the landscape [*Barker et al.*, 2019]. An eruption would also affect Lake Taupō, which fills the volcano's caldera and is the biggest freshwater lake in Australasia by volume. Lake Taupō and the surrounding volcanic landscape hold

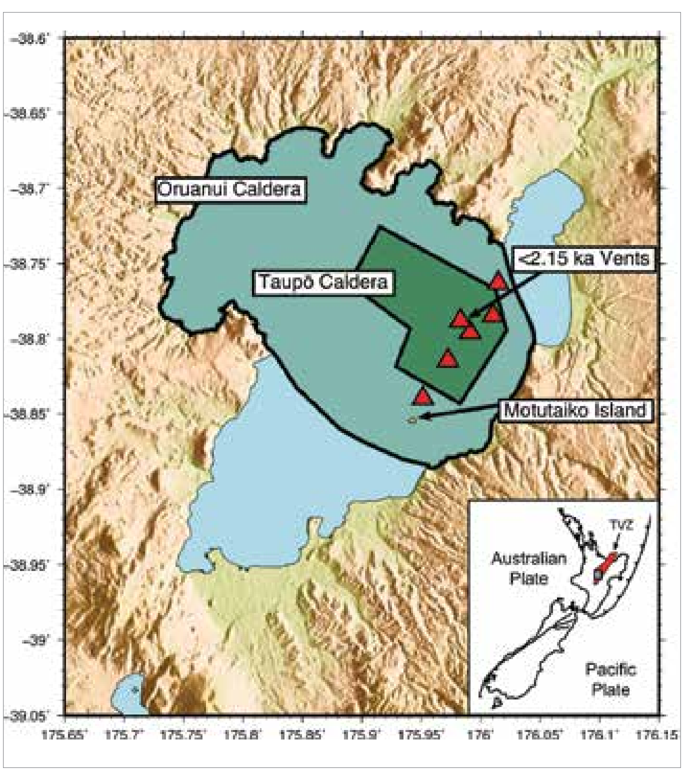


Fig. 1. Lake Taupō and its geological features. The Oruanui caldera (light green) formed 25,500 years ago, and the Taupō caldera (dark green) formed in 232 CE. Red triangles show the locations of eruptions in the past 2,150 years. TVZ = Taupō volcanic zone.

great cultural significance, especially to the Indigenous Māori people in the area. The region also provides important resources such as geothermal energy, agriculture, and forestry, and it sees more than a million tourists visit each year.

Serendipitously, the 2019 Taupō seismic unrest occurred during a research project called Eruption or Catastrophe: Learning to Implement Preparedness for future Supervolcano Eruptions (ECLIPSE), funded by the New Zealand government. ECLIPSE is a 5-year multi-institutional program designed to improve understanding of the physical state of New Zealand's caldera volcanoes (including Taupō), identify the causes of unrest and tipping points that lead to eruptions, and develop decision support tools and mitigation strategies for the island nation.

The mushy magma system below the volcano today has rebuilt to a substantial size and is capable of generating volumes of eruptible magma within only a few years to decades.

A Turbulent Past, an Uncertain Future

The modern outline of Lake Taupō formed during Earth's most recent known supereruption, the Oruanui event, which ejected more than 1,100 cubic kilometers of pumice and ash approximately 25,500 years ago [*Wilson*, 2001; *Vandergoes et al.*, 2013]. Taupō has erupted at least 28 times since then, with the largest and most recent of these events occurring in 232 CE [*Hogg et al.*, 2012], prior to the arrival of humans in New Zealand. This explosive eruption produced a high-speed flow of pumice, ash, and hot gases that devastated 20,000 square kilometers of the North Island [*Wilson and Walker*, 1985].

Variations in the composition of magmas erupted from Taupō over the past 12,000 years suggest that the mushy magma system below the volcano today has regrown to a substantial size (hundreds of cubic kilometers) and is capable of generating volumes of eruptible magma within only a few years to decades—a geologically rapid timescale [*Barker et al.*, 2015, 2016].

It is unlikely that volcanic unrest at Taupō will lead to an eruption in the near term. However, such unrest could still cause significant social and economic disruption, given the volcano's history and its reputation, which rests on the unusually large and exceptionally violent 232 CE eruption.

Signs of unrest, such as seismicity, deformation, and geothermal system changes, occur every few decades at Taupō [*Potter et al.*, 2015]. However, because the volcano is located in an active tectonic rift, where portions of crust to the west and east of the volcano are pulling apart at about 1 centimeter per year, seismicity often occurs without any direct relationship to the magmatic system beneath Taupō. The presence of the rift makes it difficult to distinguish earthquakes that are related to volcanic unrest from those that are part of the background dynamic environment.

The 2019 Seismic Swarms

In 2019, Taupō experienced its most substantial seismic activity in several decades. New Zealand's national monitoring network, GeoNet, reported more than 1,100 earthquakes within Taupō caldera during 2019, compared with the annual average of several hundred. The seismic activity occurred in discrete swarms starting in late April and culminated in a magnitude 5.2 earthquake in early September, the largest earthquake beneath the volcano since 1952.

The earthquakes occurred in locales where there is evidence of past young eruptive activity, like the 7,000-year-old lava dome called Motutaiko Island (Figure 1), and at depths of more than 5 kilometers in the crust, where Taupō's magmatic system is inferred to reside [*Barker et al.,* 2015]. Accurate earthquake detection and source location are crucial in allowing scientists to search for migrating earthquake swarms and source mechanisms suggestive of fluid interaction, both of which are telltale signs of magmatic unrest. However, the national seismic sensor network is sparse near Taupō (only five sensors are within 10 kilometers of the caldera), making it difficult to detect and locate small-magnitude earthquakes accurately, especially their depths.

As part of the ECLIPSE program and in response to the 2019 earthquake swarms, our team of researchers has installed eight additional seismometers—on loan for 2 years from the Incorporated Research Institutions for Seismology (IRIS)—around Taupō, and we are in the process of deploying another five. This will improve our understanding of and, ultimately, our capability to monitor the volcano (Figure 2). Crucially, the deployment effort is being undertaken with the full involvement of local communities and landowners as well as emergency managers and the volcano observatory—we call this a coproduction approach to research.

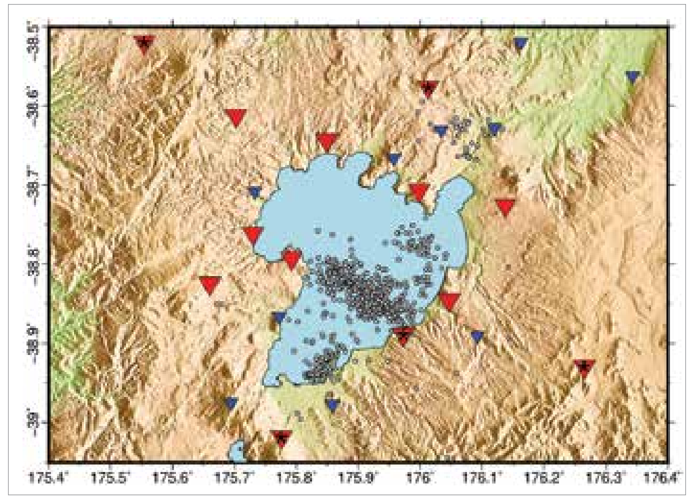


Fig. 2. Gray circles show the locations of earthquakes in the 2019 swarms, from GeoNet. Blue triangles show the GeoNet seismic network; red triangles show the Eruption or Catastrophe: Learning to Implement Preparedness for future Supervolcano Eruptions (ECLIPSE) seismic network. Asterisks denote planned sites.

Working with the People of the Land

Land ownership has been a contentious issue in New Zealand since European colonization, stemming largely from the differing views and interpretations of land ownership between the Indigenous Māori peoples and colonizers. The Ngāti Tūwharetoa iwi (tribe) are the kaitiaki (guardians) of the Taupō region, and they have a deep sense of belonging to and inherent responsibility for the land. This relationship extends beyond notions of land ownership conventional in Western cultures and is more closely described as the people belonging to the maunga (mountains), moana (lake), and whenua (land).

Because of this, our research is intrinsically linked to understanding Ngāti Tūwharetoa's whenua and taonga (cultural treasures). Installing seismometers can be viewed as intrusive, so we have sought to ensure that the Indigenous community is aware of, and approves of, our research techniques. For example, all of the new seismometer locations have been planned alongside the hapū (family groups) that have dominion over each site. This approach has engaged the hapū in our work and has allowed us to avoid impinging on waahi tapu (sacred sites), including burial sites, former settlements, and sacred landscapes. This consultation is vital because the locations of the numerous culturally significant sites around the lake are generally not known to people outside the iwi.

Our coproduced research represents a modern approach to volcano science in

Looking south across a calm Lake Taupō toward Motutaiko island and the andesite volcanoes of the Tongariro National Park. Motutaiko island is a 7,000-year-old lava dome and has great cultural significance for the Ngāti Tūwharetoa iwi. Credit: Colin J. N. Wilson

Simon Barker, Eleanor Mestel, and Martha Savage install an ECLIPSE seismometer on the northern shore of Lake Taupō in October 2019. Credit: Finnigan Illsley-Kemp

New Zealand, and it opens the opportunity for a level of outreach and engagement in the local community that has not previously been achieved. Conveying the concept of volcanic hazards is, however, a challenge in the context of the Māori worldview (Te Ao Māori), which posits the people as direct descendants of their whenua and maunga. Māori communities might not be receptive to the idea that these landscapes could pose hazards to the people, so hazard communication methods familiar to most Westerners are not effective.

Māori communities might not be receptive to the idea that landscapes could pose hazards to the people, so hazard communication methods familiar to most Westerners are not effective.

Western concepts of science are often presented to Indigenous communities without much thought about cultural differences in how scientific knowledge is received and digested. The ECLIPSE project, however, includes Māori and other researchers who are investigating the effectiveness of science dissemination in communities in New Zealand as well as how we can integrate the Māori worldview into our science communication. With the findings from these efforts, we will be able to engage and inform the population living around the volcano more effectively and meaningfully. Our coproduction approach is also relevant for research in other countries, and we hope it contributes to helpful collaborations between Indigenous peoples and scientists elsewhere.

Improved Understanding of Taupō

The new seismic network will dramatically increase the station coverage around Taupō. We have two main ambitions here: improved detection and location of earthquakes and direct imaging of the magma system beneath the lake. With the current GeoNet seismic network at Taupō, the earthquake catalog is complete only above magnitude 2.2, meaning that many smaller earthquakes are missed and accurately locating earthquake sources is problematic. Therefore, trying to understand geodynamic activity and define unrest events at Taupō has been challenging.

The addition of the new ECLIPSE seismic network will significantly improve the detection threshold and increase the size of the earthquake catalog for events in the Taupō area, allowing us to track seismicity and volcanotectonic behavior in much greater detail. The network will also allow researchers to directly image the magma system beneath Taupō using geophysical techniques. Because the system is concealed beneath Lake Taupō, this imaging has not been achieved before, resulting in uncertainties regarding the volume and current physical state of the magmatic system [*Barker et al.,* 2015].

We will use the expanded earthquake catalog, alongside measurements of the ambient seismic noise field, to perform a joint inversion analysis of seismic velocities and create the first 3-D image of the crust beneath Taupō. This work should help reveal the extent and depth of the magmatic system and, potentially, details about its internal structure. It will also enable us to interpret earthquake activity, such as the 2019 seismic swarms, in the context of the magma system location and physical state. Such information is vital for considering the processes responsible for unrest at Taupō, making plausible estimates of future eruption sizes and locations, and providing appropriate advice through GeoNet to Ngāti Tūwharetoa, civil authorities, emergency managers, and the public.

References

Barker, S. J., et al. (2015), Fine-scale temporal recovery, reconstruction and evolution of a post-supereruption magma system, *Contrib. Mineral. Petrol., 170,* 5, https://doi.org/10.1007/s00410-015-1155-2.

Barker, S. J., et al. (2016), Rapid priming, accumulation, and recharge of magma driving recent eruptions at a hyperactive caldera volcano, *Geology, 44,* 323–326, https://doi.org/10.1130/G37382.1.

Barker, S. J., et al. (2019), Modeling ash dispersal from future eruptions of Taupo supervolcano, *Geochem. Geophys. Geosyst., 20,* 3,375–3,401, https://doi.org/10.1029/2018GC008152.

Hogg, A. G., et al. (2012), Revised calendar date for the Taupo eruption derived by ^{14}C wiggle-matching using a New Zealand kauri ^{14}C calibration data set, *Holocene, 22,* 439–449, https://doi.org/10.1177/0959683611425551.

Potter, S. H., et al. (2015), A catalogue of caldera unrest at Taupo Volcanic Centre, New Zealand, using the volcanic unrest index (VUI), *Bull. Volcanol., 77,* 78, https://doi.org/10.1007/s00445-015-0956-5.

Vandergoes, M. J., et al. (2013), A revised age for the Kawakawa/Oruanui Tephra, a key marker for the Last Glacial Maximum in New Zealand, *Quat. Sci. Rev., 74,* 195–201, https://doi.org/10.1016/j.quascirev.2012.11.006.

Wilson, C. J. N. (2001), The 26.5 ka Oruanui eruption, New Zealand: An introduction and overview, *J. Volcanol. Geotherm. Res., 112,* 133–174, https://doi.org/10.1016/S0377-0273(01)00239-6.

Wilson, C. J. N., and G. P. L. Walker (1985), The Taupo eruption, New Zealand I. General aspects, *Philos. Trans. R. Soc. London, Ser. A, 314,* 199–228, https://doi.org/10.1098/rsta.1985.0019.

Author Information

Finnigan Illsley-Kemp (finnigan.illsleykemp@vuw.ac.nz) and **Simon J. Barker,** School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand; **Bubs Smith,** Ngāti Tūwharetoa, Turangi, New Zealand; and **Colin J. N. Wilson,** School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand

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

THE FUTURE OF THE CARBON CYCLE IN A CHANGING CLIMATE

By Aleya Kaushik, Jake Graham, Kalyn Dorheim, Ryan Kramer, Jonathan Wang, and Brendan Byrne

Interacting feedbacks, anthropogenic impacts, and other complex effects require a holistic understanding of the ways that Earth's many systems absorb and release carbon.

belyaaa/stock.adobe.com. Opposite, left to right: iStock.com/Drbouz; Unsplash/Paolo Nicolello; iStock.com/Shubham Singh

Over the past 50 years, a growing wealth of long-term atmosphere, ocean, and ecosystem observations has provided essential insights into how climate change affects the ways that carbon moves through Earth's environment, yet many fundamental questions remain unanswered. Perhaps the most challenging and societally relevant question is whether the rate at which the land and ocean can sequester carbon will continue to keep pace with rising carbon dioxide emissions.

Emissions of carbon dioxide (CO_2) and methane (CH_4) stemming from human activities are rapidly and dramatically altering Earth's climate. Warmer temperatures drive longer and more destructive fire seasons, shifting precipitation patterns cause flooding in some areas and drought in others, and ocean acidification threatens marine life across the globe.

However, land and ocean ecosystems act as natural buffers that limit the increase of CO_2 in the atmosphere by absorbing and sequestering nearly half of emitted CO_2. Although anthropogenic greenhouse gas emissions continue to increase, this natural climate change mitigation has so far proportionally kept pace with emissions, limiting global warming to a certain extent (Figure 1).

This situation could change, however. For example, although tropical forests in the Amazon have been CO_2 sinks over the past 50 years, increasing land use change, drought, fires, and tree deaths in recent years may have tipped the balance, making this region a periodic net carbon source [*Yang et al.*, 2018]. Arctic observations, mean-

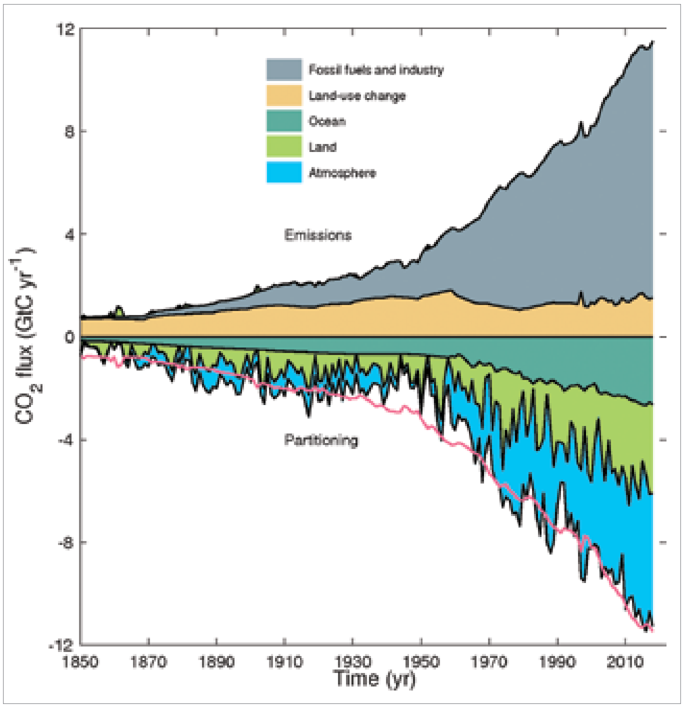


Fig. 1. Carbon dioxide fluxes (in gigatons of carbon per year, GtCyr^{-1}) of major anthropogenic sources (positive) and natural sinks (negative) demonstrate the corresponding increases in both from 1850 to 2017. The difference between the pink curve (a mirror image of the total emissions curve above) and the curve representing the sum of ocean, land, and atmosphere sinks indicates a budget imbalance reflecting a gap in our understanding. Credit: Friedlingstein et al., *2019, CC BY 4.0 (bit.ly/ccby4-0)*

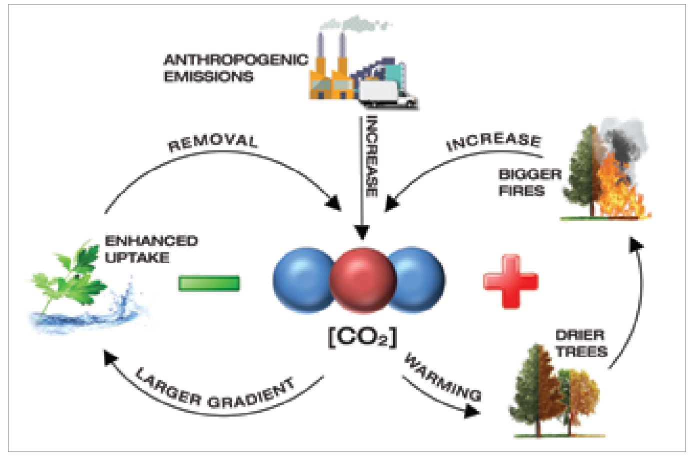


Fig. 2. In the negative carbon-climate feedback (left), increasing carbon dioxide (CO_2) concentrations stimulate plants to take up carbon from the atmosphere, which lowers the atmospheric concentration and causes a stabilizing effect. Conversely, in the positive feedback (right), higher temperatures from increasing atmospheric CO_2 concentrations cause drying of vegetation, leading to increased fire frequency and severity, which releases more carbon to the atmosphere, resulting in an amplifying effect. Credit: The authors and David Hinkle, NASA/JPL-Caltech

while, have revealed little change in long-term CH_4 emissions from the region so far. However, Arctic warming has occurred at double the average global rate [*Intergovernmental Panel on Climate Change*, 2014], and the resulting abrupt permafrost thaw events and increased winter emissions could lead to a tipping point by the mid-21st century [*Turetsky et al.*, 2019].

Decades of global measurements can now help address two key questions: (1) How do ecosystems respond to climate change? (2) How will these ecosystem responses change Earth's carbon budget in the future?

Interacting Processes Introduce Complexity

Predicting interactions between Earth's climate and carbon cycle is challenging because of the number of feedbacks involved. Carbon cycle feedbacks are interacting processes that amplify or dampen carbon emissions.

Direct carbon cycle feedbacks are driven solely by increasing atmospheric CO_2 concentrations. For example, increasing atmospheric CO_2 increases the efficiency of photosynthesis and promotes plant growth, sequestering atmospheric CO_2; this dampening is a negative feedback. Similarly, increasing atmospheric CO_2 increases the concentration gradient between the atmosphere and the ocean, driving carbon dissolution into the ocean and sequestering atmospheric CO_2.

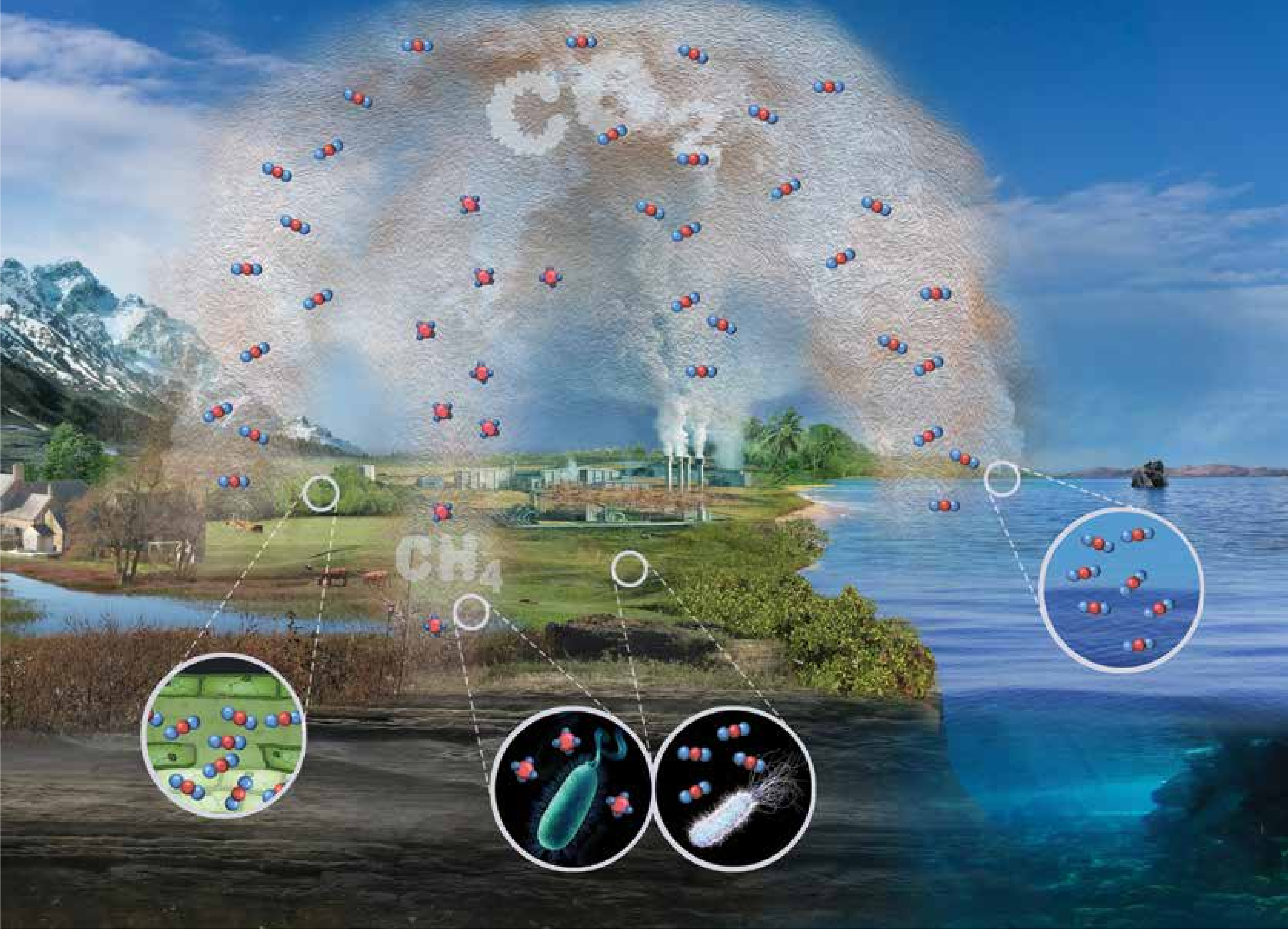
Indirect feedbacks influence carbon exchange via ecosystem responses to climate change and are referred to as carbon-climate feedbacks. For example, CO_2 is less soluble in warmer water; thus, warmer oceans absorb less CO_2, meaning that more CO_2 remains in the atmosphere. This, in turn, leads to further warming in a process known as a positive feedback. Warmer temperatures lead to longer growing seasons and reduce atmospheric CO_2 through photosynthetic uptake by plants, but warming also increases plant and soil respiration, water stress, drought, disturbance, and forest dieback, which reduce CO_2 uptake and increases the risk and severity of wildfires (Figure 2).

Methane is produced by organisms that do not use oxygen to convert nutrients into energy (anaerobic respiration), and it is removed by oxidation in the atmosphere. Although CH_4 is a small component of the overall carbon budget, it is a potent greenhouse gas, and changes in atmospheric CH_4 are of great concern. Changes in wetland extent due to changing precipitation in the tropics and warming-induced permafrost thaw in the Arctic could lead to large changes in CH_4 production [*Zhang et al.*, 2017]. Thawing Arctic permafrost, in particular, has been cited as a potentially major positive feedback, where thawing leads to increased CH_4 release, driving warming and more permafrost thaw.

The Carbon Cycle from Many Vantages

Our understanding of carbon-climate feedbacks is built on long-running observational networks and ecosystem manipulation studies, ranging from site-level, bottom-up experiments across a variety of ecosystems to global, space-based, top-down measurements.

Since the late 1950s, atmospheric CO_2 measurements from the Scripps Institution of Oceanography and, later, the Earth System Research Laboratory's global network of surface stations have provided continental- to global-scale constraints on CO_2 exchanges between the land and the atmosphere. These measurements constitute precise estimates of atmospheric CO_2 concentration and provide a constraint on the partitioning of anthropogenic CO_2 emissions between different regions. They also help scientists identify emerging trends such as the increasing seasonal amplitude of carbon uptake and release by Northern Hemisphere ecosystems



Earth's global carbon cycle includes major carbon sinks and sources. (Inset diagrams show key processes in the carbon cycle, such as plant and microbial respiration and ocean–atmosphere exchange.) Decades of global measurements can now help us understand how ecosystems respond to climate change and how this response will change the carbon budget in the future. Credit: The authors and David Hinkle, NASA/JPL-Caltech

since the 1960s [*Keeling et al.,* 1996]. Recently, space-based measurements of atmospheric CO_2 have greatly expanded observational coverage, particularly in the tropics, allowing for more resolved estimates of CO_2, although ground-based truthing of satellite data remains challenging.

Another important data set comes from the global FLUXNET network of eddy covariance flux towers. This network, comprising hundreds of instrument towers across many different ecological settings, uses micrometeorological observations to estimate exchanges of water, energy, and carbon across entire ecosystems and over a span of decades. Over this period, these towers have captured a wide range of environmental variability, providing insights into the sensitivity of plant and soil physiology to changes in temperature, humidity, and disturbance events like fires and land use change [*Baldocchi,* 2019]. FLUXNET is an essential tool for expanding our understanding of plant physiology to the landscape scale.

Complementing these observations are ecosystem manipulation experiments, which monitor responses to imposed environmental changes. At Free Air CO_2 Enrichment (FACE) sites, researchers artificially raise CO_2 levels in small areas containing whole ecosystems by pumping CO_2 from towers into the air below to mimic future atmospheric conditions. Data from these experiments provide direct evidence of increasing photosynthetic uptake with CO_2 fertilization and the potential for nutrient shortages to limit this fertilization [*Leakey et al.,* 2009].

Similarly, warming studies (e.g., Spruce and Peatland Responses Under Changing Environments) manipulate soil temperature to elucidate potential positive feedbacks from soil respiratory carbon losses under climate warming [*Carey et al.,* 2016]. FACE and warming studies provide some of the most direct evidence of ecosystem sensitivity to future climates. However, both FLUXNET and FACE sites are limited to northern midlatitude ecosystems, in part because of logistical constraints and in part because that's where most of the scientists are. Thus, there are observational gaps in climate-sensitive tropical, boreal, and Arctic ecosystems.

Space-based observing systems are an essential complement to site-level measurements, allowing researchers to monitor ecosystem function across continents and identify critical regions and scales for carbon cycling. With multidecadal satellite remote sensing records, it has become possible to distinguish interannual variability from trends. For example, the widespread "greening" of northern high latitudes may indicate increased vegetation productivity in response

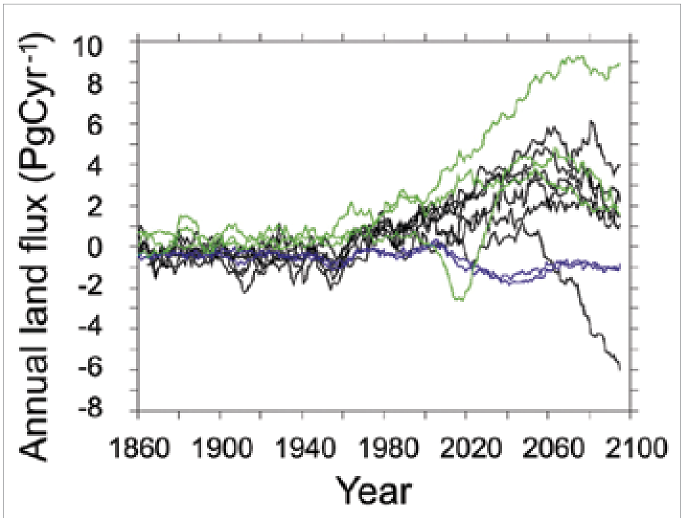


Fig. 3. Global atmosphere-to-land carbon fluxes (in petagrams of carbon per year, $PgCyr^{-1}$) from 11 emission-driven Earth system model simulations show divergent predictions. Discrepancies among models are attributed to uncertainty in the response of the terrestrial carbon cycle related to carbon-climate feedbacks. Credit: Friedlingstein et al., *2014 © American Meteorological Society. Used with permission.*

to CO_2 fertilization or warming [*Mao et al.*, 2016]. Remote sensing time series can also detect and quantify areas of disturbance and land use change, revealing the extent to which warming-induced increases in fires and insect disturbance may cause forests to transition from carbon sinks to carbon sources.

Observational systems monitoring ocean chemical and physical processes are also critical for understanding the ocean carbon cycle. Current ocean observing systems include ship-based measurements, the Argo floats network, and surface buoys from the Global CO_2 Time-Series and Moorings Project. These systems measure surface water CO_2 and temperature and, in conjunction with atmospheric observations, provide evidence of surface ocean carbon exchange through wind-driven upwelling and transport.

Satellite-based microwave sensors can be used to infer additional surface ocean properties influencing air-sea exchange, such as rain, wind speed, sea state, and salinity. These properties influence density-driven thermohaline circulation originating in high latitudes, which is principally responsible for relocating CO_2 into the deep ocean, where it is stored for several hundred years. Changes in precipitation that increase river runoff and warmer temperatures that melt sea ice may freshen high-latitude surface oceans. This freshening may result in less overturning of the layers of water in the oceans, thus slowing thermohaline circulation and carbon removal.

A Struggle for Consistency

Different methods of carbon flux observations do not always produce consistent results: There is an emerging chasm between constraints on carbon cycling derived from small-scale and large-scale observations: Not only do the physical processes differ at different scales, but also different experimental methods and data sources produce different results. For example, multidecadal site-level observations at FLUXNET sites do not clearly show that plants increase their carbon uptake in response to CO_2 fertilization, but they do confirm that plant and soil respiration are sensitive to temperature, suggesting that warming will lead to carbon loss from the biosphere. Furthermore, because of regional observational gaps, data upscaling methods trained on these sites (e.g., FLUXCOM) estimate unrealistically large carbon sinks in the tropics [*Tramontana et al.*, 2016]. In contrast, top-down constraints from atmospheric CO_2 measurements show trends of increasing carbon uptake by unmanaged ecosystems in both the tropics and northern extratropics.

Reconciling these conflicting results is challenging because of the extreme difference in scales between bottom-up and top-down estimates and heterogeneity among ecosystems. Resolving the discrepancies requires both more site-level observations in relatively undersampled regions and continued investment in space-based satellite observations, which are crucial for monitoring regional changes in carbon uptake.

Just as observational methods produce different results, current terrestrial ecosystem models indicate different trends in carbon uptake (Figure 3), limiting our understanding of the evolution of carbon-climate feedbacks [*Friedlingstein et al.*, 2014]. This divergence is partly due to complexities in simulating biogeochemical systems and their sensitivity to climate. It also arises from incomplete representation of complex land-atmosphere interactions, such as water stress impacts from repeated droughts and shifts in precipitation.

Yet both process-based and empirical models remain key for understanding recent changes and projecting future climate and carbon cycle changes. Increasingly complex models with sophisticated representations of dynamic vegetation, plant hydraulics, and disturbances are under development, but because of this increasing complexity, they are more challenging to validate.

The International Land Model Benchmarking Project provides an attempt to formalize model validation by developing systematic methods for confronting a variety of models with a standard set of observations to advance model development. An emerging area of research deals with optimizing parameterizations within terrestrial biosphere models by assimilating quantities such as soil moisture, solar-induced chlorophyll fluorescence, and variation in atmospheric CO_2 [*Scholze et al.*, 2017], providing additional observational constraints on parameter uncertainty. However, this technique cannot account for errors in model structure.

Ocean modeling studies will benefit from increased resolution and better representation of critical processes such as eddies, brine plumes, and formation of oxygen minimum zones. Decreased vertical mixing and increased stratification due to surface ocean warming both reduce upwelling, which is critical for providing nutrients to the surface ocean. During El Niño–Southern Oscillation (ENSO) events, nutrient shortages can cause fisheries to collapse. Although ENSO events are a natural part of the ocean-atmosphere climate system, their global teleconnections drive interannual variability in the carbon cycle [*Liu et al.*, 2017], and the evolution of ENSO with climate change is uncertain.

Unintended Consequences of Mitigation

Developing and implementing technologies to remove CO_2 from the atmosphere are key for limiting global temperature rise to less than 2°C above preindustrial levels, the benchmark determined in the 2016 Paris Agreement. However, carbon capture may have unintended consequences by affecting concentration-driven direct carbon feedbacks. Decreased atmospheric CO_2 will reduce CO_2 fertilization and ocean carbon uptake, potentially reversing natural carbon sequestration [*Keller*

Aerial and inner chamber views of the Department of Energy's Spruce and Peatland Responses Under Changing Environments experiment, where whole-ecosystem warming is coupled with intentional CO_2 enrichment in open-top enclosures to simulate future environmental conditions. The study aims to evaluate how carbon-rich peatlands will respond to environmental change. Credit: Oak Ridge National Laboratory (left); The PhenoCam Network (right), CC BY 3.0 (bit.ly/ccby3-0)

et al., 2018]. These effects will counter mitigation strategies, making them appear less effective.

Understanding these complex feedback–mitigation interactions is important not only for stakeholders who assess mitigation scenarios but also for those tasked with clearly communicating the expectations of mitigation strategies to the public. If expected changes are not communicated well, muted reductions in atmospheric CO_2 after the implementation of mitigation might be misinterpreted as failures or shortcomings of mitigation efforts. Mitigation strategy planning must account for both rising CO_2 emissions and reduced efficacy of natural CO_2 sinks.

An emerging area of carbon cycle research examines human and economic responses, which are an indirect form of feedback. Climate-driven decreases in economic activity could decrease emissions in some sectors—an example of a negative carbon-climate-economic feedback. New modeling frameworks designed around Shared Socioeconomic Pathways attempt to integrate human responses into Earth system models to account for the interactions between population, economic growth, energy system parameters, land use, emissions, and concentrations [*Riahi et al.*, 2017].

Just as observational methods produce different results, current terrestrial ecosystem models indicate different trends in carbon uptake.

Investing in Measurements and Models

Looking forward, it's likely that potential nonlinear, time-dependent, and state-dependent feedbacks and responses in the carbon cycle will remain difficult to predict, particularly because many feedbacks interact with each other. Investments should be made to continue observations with existing networks and observing systems and to expand these sorts of observations to undersampled regions (e.g., the Arctic and tropics). And new types of measurements (e.g., of carbonyl sulfide and solar-induced fluorescence) that can provide new perspectives on ecosystem processes should be explored.

Including socioeconomic responses to climate change in Earth system models will also be critical for understanding future changes to the climate and carbon cycle. Anthropogenic CH_4 emissions are ultimately tied to how we grow food (e.g., in rice paddies and cattle feed lots), deal with waste (e.g., in landfills), and produce energy (e.g., via oil and gas extraction)—all essential activities for civilization. Mitigating CH_4 emissions in response to climate change will impact economic activity, an example of emerging climate socioeconomic feedbacks.

Finally, a large spread in future carbon uptake is predicted by terrestrial biosphere models, suggesting that they do not yet have sufficient skill to offer precise predictions of future uptake at fine scales and into the far future. Further development of evaluation metrics and improved model representations of Earth system processes are thus crucial for understanding recent changes, projecting further into the future (e.g., to 2300), and identifying which data are key to collect.

Acknowledgments

This feature is largely based on the science presentations and discussions at the AGU Chapman Conference on Understanding Carbon-Climate Feedbacks, which took place in La Jolla, Calif., in August 2019. A.K. was supported by a Cooperative Institute for Research in Environmental Sciences postdoctoral appointment, administered by the University of Colorado Boulder.

B.B. was supported by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, California Institute of Technology, administered by the Universities Space Research Association under contract with NASA. J.W. was supported by the University of California National Laboratory Fees Research Program, administered by the University of California Office of the President. J.G. was supported by Boise State University and Oak Ridge National Laboratory (contract 4000145196). K.D. was supported by the NASA Carbon Monitoring System (grant NNX16AQ55G). R.K. was supported by an appointment to the NASA Postdoctoral Program at NASA Goddard Space Flight Center, administered by the Universities Space Research Association.

References

Baldocchi, D. (2019), How eddy covariance flux measurements have contributed to our understanding of *Global Change Biology*, *Global Change Biol., 26,* 242–260, https://doi.org/10.1111/gcb.14807.

Carey, J. C., et al. (2016), Temperature response of soil respiration largely unaltered with experimental warming, *Proc. Natl. Acad. Sci. U. S. A., 113*(48), 13,797–13,802, https://doi.org/10.1073/pnas.1605365113.

Friedlingstein, P., et al. (2014), Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks, *J. Clim., 27*(2), 511–526, https://doi.org/10.1175/JCLI-D-12-00579.1.

Friedlingstein, P., et al. (2019), Global carbon budget 2019, *Earth Syst. Sci. Data, 11,* 1,783–1,838, https://doi.org/10.5194/essd-11-1783-2019.

Intergovernmental Panel on Climate Change (2014), *Climate Change 2014: Synthesis Report—Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by Core Writing Team, R. K. Pachauri, and L. A. Meyer, 151 pp., Geneva, Switzerland, ar5-syr.ipcc.ch/.

Keeling, C. D., J. F. S. Chin, and T. P. Worf (1996), Increased activity of northern vegetation inferred from atmospheric CO_2 measurements, *Nature, 382,* 146–149, https://doi.org/10.1038/382146a0.

Keller, D. P., et al. (2018), The effects of carbon dioxide removal on the carbon cycle, *Curr. Clim. Change Rep., 4,* 250–265, https://doi.org/10.1007/s40641-018-0104-3.

Leakey, A. D., et al. (2009), Elevated CO_2 effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE, *J. Exp. Bot., 60*(10), 2,859–2,876, https://doi.org/10.1093/jxb/erp096.

Liu, J., et al. (2017), Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño, *Science, 358*(6360), 191–198, https://doi.org/10.1126/science.aam5690.

Mao, J., et al. (2016), Human-induced greening of the northern extratropical land surface, *Nat. Clim. Change, 6,* 959–963, https://doi.org/10.1038/nclimate3056.

Riahi, K., et al. (2017), The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, *Global Environ. Change, 42,* 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Scholze, M., et al. (2017), Reviews and syntheses: Systematic Earth observations for use in terrestrial carbon cycle data assimilation systems, *Biogeosciences, 14,* 3,401–3,429, https://doi.org/10.5194/bg-14-3401-2017.

Tramontana, G., et al. (2016), Predicting carbon dioxide and energy fluxes across global FLUXNET sites with regression algorithms, *Biogeosciences, 13,* 4,291–4,313, https://doi.org/10.5194/bg-13-4291-2016.

Turetsky, M., et al. (2019), Permafrost collapse is accelerating carbon release, *Nature, 569,* 32–34, https://doi.org/10.1038/d41586-019-01313-4.

Yang, Y., et al. (2018), Post-drought decline of the Amazon carbon sink, *Nat. Commun., 9,* 3172, https://doi.org/10.1038/s41467-018-05668-6.

Zhang, Z., et al. (2017), Emerging role of wetland emissions in driving 21st century climate change, *Proc. Natl. Acad. Sci. U. S. A., 114*(36), 9,647–9,652, https://doi.org/10.1073/pnas.1618765114.

Author Information

Aleya Kaushik (aleya.kaushik@noaa.gov), Global Monitoring Division, National Oceanic and Atmospheric Administration, Boulder, Colo.; **Jake Graham,** Boise State University, Boise, Idaho; **Kalyn Dorheim,** Pacific Northwest National Laboratory, Richland, Wash.; **Ryan Kramer,** NASA Goddard Space Flight Center, Greenbelt, Md.; **Jonathan Wang,** University of California, Irvine; and **Brendan Byrne,** NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena

▶ Read the article at bit.ly/Eos-carbon

AGU's Online Learning Exchange Shares Education Resources

Unsplash/Johnson Wang

Led by the experts in our Education section, AGU has developed the Online Learning Exchange so that educators can share the tools and tips they are using to keep teaching in the classroom, lab, and field.

AGU members and nonmembers around the world are encouraged to engage by doing the following:

- Fill out a 13-question form to tell us what tool or technology you use and how you think others would benefit from it (bit.ly/ESS-teaching-suggestions)
- Discuss any tips or tricks—or ask for advice—for everything from keeping students engaged to maintaining your own well-being (bit.ly/AGU-learning-exchange)
- Tell us how COVID-19 has changed your work (bit.ly/AGU-covid-survey)
- Publish your poster or research virtually via ESSOAr, an AGU-led preprint server (bit.ly/essoar)
- Network with colleagues in your field or in other areas by filling out an AGU.org profile. Members and nonmembers can create an AGU.org profile with their bio, social media accounts, organization affiliations, scientific interests, and needs from AGU.

We will share your responses across our many digital platforms, including AGU's website, Connect, blog, and social media channels. In addition to the resources at the Online Learning Exchange, remember we have articles on Eos.org about recent research in every field of Earth and space sciences, which you can print to PDF or email directly to students.

Visit the Online Learning Exchange at bit.ly/online-learning-exchange to use our resources and stay connected. ■

The Stuff That Psyche Is Made Of

Psyche is a large, peculiar asteroid that orbits the Sun in our solar system's asteroid belt. Although most asteroids are made primarily of rock or ice, Psyche is abundant in metal, suggesting that it could be the remnant core of an early planet. Now *Elkins-Tanton et al.* report that Psyche may have a higher ratio of rock to metal than previously hypothesized.

In preparation for a NASA mission to Psyche set to launch in 2022, the researchers reviewed and analyzed reports on the latest observations of the asteroid, which included data from mass and volume calculations, radar measurements, and investigations of Psyche's spectral signature.

The analysis suggests that Psyche, which is about 226 kilometers in diameter, has a density of 3,400–4,100 kilograms per cubic meter. And although earlier observations suggested that the asteroid consists almost entirely of iron and nickel, it now appears that those metals make up only 30%–60% of its volume, with the rest consisting of silicate rock and pore space.

The origin of Psyche, the details of its structure, and the specific kinds of rock it contains remain mysterious. Is Psyche indeed the core of an early planet that was stripped of its outer layers by impacts with other objects? If so, what did that planet look like, and what kinds of collisions and other conditions shaped its fate? Or did it form in some previously unimagined scenario?

The new findings help constrain the possible answers to these questions, providing valuable context for the upcoming mission to Psyche—the first mission to a metallic asteroid. Observing Psyche up close should provide final answers about the asteroid and could improve understanding of how Earth and other planets formed. (*Journal of Geophysical Research: Planets,* https://doi.org/10.1029/2019JE006296, 2020) **—Sarah Stanley,** *Science Writer*

While preparing for an upcoming NASA mission to observe the asteroid Psyche up close, scientists have uncovered new insights into the composition and origin of this enigmatic asteroid. Credit: ASU/P. Rubin/NASA

Improving Climate Predictions over Decades

Earth's climate system is chaotic and nonlinear. These characteristic impose limits on how well scientists can predict climate statistics related to temperature, precipitation, and other variables. (The degree to which skillful predictions can be made is called predictability.) The steady evolution of climate modeling over the past several decades has led to significant strides in seasonal climate prediction, but forecasting the climate over decades has proved more challenging.

At the timescale of decades, climate swings are driven by both internal dynamics, like the El Niño–Southern Oscillation, and external factors (e.g., volcanic eruptions). The limits and mechanisms of these phenomena are still not fully understood, which imposes boundaries on the climate's long-term predictability.

Zhang and Kirtman recently explored climate predictability over decades. The authors applied an interactive ensemble coupling strategy to the Community Climate System Model (CCSM4) to create climate simulations with decreased atmospheric noise at the air-sea interface. In other words, they reduced short-term variability in the climate model. By reducing this noise, the authors isolated the climate signal in the model and were able to quantify how the noise affects predictability. To measure predictability, they used the nonlinear local Lyapunov exponent (NLLE) method, which was the first use of NLLE with state-of-the-art coupled climate models.

The study determined that the interactive ensemble approach underestimates decadal predictability compared with estimates generated from observational data. However, the results indicated that predictability varies by region. Forecasts from the North Atlantic Ocean were more predictable, for instance, whereas the Indian and Southern oceans were less predictable than the control simulations.

The authors also evaluated the predictability of subsurface ocean temperature in the North Atlantic. In regions without external climate forcings, the interactive ensemble method resulted in decreased predictability. In areas with both internal and external dynamics, predictability increased. The mechanisms for these patterns, however, require further investigation.

Although the study does not solve the challenge of long-term predictability of climate models, the findings do suggest that decadal predictability is related to both internal climate variability and ocean dynamics. (*Geophysical Research Letters,* https://doi.org/10.1029/2018GL081307, 2019) **—Aaron Sidder,** *Science Writer*

Reforestation as a Local Cooling Mechanism

Reforested lands like North Carolina's Duke Forest represent an important tool for mitigating climate change. Trees both sequester carbon from the atmosphere and cool surface and air temperatures locally. Credit: Jenna Schreiber, Office of the Duke Forest

Temperate forests have a reputation as crucial global carbon sinks. In fact, research suggests that American forests alone suck up the equivalent of 14% of annual carbon dioxide emissions in the United States. And after decades of net global forest loss, reestablishing forests worldwide is viewed as a viable option for mitigating the effects of climate change.

Beyond the carbon sequestration potential of reforestation, in many parts of the world, forests offer the added benefit of reducing surface temperatures by drawing water from the atmosphere and increasing heat transfer away from the surface. At a local level, restoring forests may help alleviate the effects of climate warming.

There is a distinction, however, between surface temperature and air temperature, and the science remains unclear as to whether reforestation also successfully lowers air temperature. Whereas surface temperature is measured only at the surface, air temperature changes with height and may be influenced by changes in wind patterns caused by the forest canopy.

In a new study, *Novick and Katul* describe a novel approach to investigating both surface and air temperature on the basis of flux tower observations. The method accounts for canopy effects and uses tower measurements to estimate multiple metrics that link surface and air temperature. The research was conducted using data from three AmeriFlux sites in the Duke Forest in North Carolina. The researchers compared observations from colocated grassland, pine forest, and hardwood forest ecosystems, which represent the three phases of ecological succession in the region.

The study found that although air cooling from forests is not as significant as cooling on the surface, forest canopies still reduce air temperature near the surface by 0.5°C–1°C over a year. During the growing season, the warmest time of the year, forests reduce daytime near-surface air temperatures by 2°C–3°C. However, the effect is minimal at night.

By focusing on air and surface temperature, the study offers a more complete picture of how forests regulate temperature and cool landscapes than previous studies. The results should help communities better understand the benefits of reforestation and its upside as a climate mitigation tool. (*Journal of Geophysical Research: Biogeosciences,* https://doi.org/10.1029/2019JG005543, 2020) **—Aaron Sidder,** *Science Writer*

A More Accurate Global River Map

Mapping all of the world's rivers, creeks, and streams is a daunting task, particularly in places like the Arctic, where accurate topographic data are hard to obtain. Scientists now have created a new map of global rivers based on a largely automated computer algorithm that can accurately predict where rivers flow—a tool that could help project future flooding as Earth's climate changes.

Many different factors affect the flow of water over land, including terrain steepness, watershed size, and human-built structures like canals. Scientists have previously used topographic data collected by spacecraft such as NASA's Shuttle Radar Topography Mission to generate detailed, 3-D models of Earth's surface, but these maps sometimes distort the slope of local terrain due to observation errors.

In the new study, *Yamazaki et al.* used an updated version of a popular topographic data set called the Multi-Error-Removed Improved-Terrain Digital Elevation Model (MERIT DEM), which was published in 2017 by members of the same team, to develop a computer algorithm that predicts where rivers flow with very little human guidance. The new, publicly available hydrographic data set, called MERIT Hydro, reveals rivers at high resolution in approximately 90- × 90-meter gridded pixels, includes the Arctic region, and is less prone to errors caused by tree canopies or inaccurate elevation than existing global hydrographic maps, the authors write. Compared with existing maps, the synthetic hydrographic maps made remarkably accurate predictions of where rivers, such as China's Pearl River and the Ob River in Russia, should be, the team reported.

To further refine the map, the team also included global Landsat data, as well as data from the crowdsourced mapping database OpenStreetMap, which the researchers searched using tags such as "waterway," "river," "stream," "brook," and "wadi." On the basis of this combined data set, the algorithm integrated information on small streams not captured by current satellite images. The OpenStreetMap data also allowed the researchers to generate maps of human-made stream networks, like irrigation canals, that could be flood prone.

A remaining challenge for more accurate river mapping is in arid regions such as the Danakil Desert in Ethiopia, where streams are often intermittent and ephemeral, the researchers noted.

The team writes that it hopes other scientists will build upon and improve the free, open-source MERIT Hydro program, noting that it could be used in predicting flood risks and analyzing ecosystem biodiversity and carbon emissions. (*Water Resources Research,* https://doi.org/10.1029/2019WR024873, 2019) **—Emily Underwood,** *Science Writer*

Big Data Help Paint a New Picture of Trace Element Cycling

Although trace metals such as iron, copper, and zinc occur only in extremely low concentrations in the world's oceans, they play an essential role in regulating photosynthesis and the global carbon cycle. But the difficulties inherent in measuring such minute concentrations, as well as the large uncertainties that exist regarding micronutrients' sources and sinks—including their uptake and release from particulate phases—have made it challenging for scientists to quantify these complex biogeochemical cycles.

Now *Ohnemus et al.* present a novel conceptual framework for interpreting and understanding particulate trace metal data. Using extensive measurements of trace element distributions extracted from GEOTRACES biogeochemical data sets, the researchers show that simple statistical regressions—the conventional approach for modeling ocean particulate distributions—don't accurately represent most trace metal cycles in the South Pacific and North Atlantic Oceans. They then demonstrate how alternative statistical techniques such as factor analysis, which allows scientists to examine biogeochemical processes that affect multiple trace elements at the same time, are much more effective at meaningfully interpreting large data sets.

The results indicate that although no two trace metals respond in the same way to the processes controlling their cycling, key processes such as biological uptake and remineralization do affect groups of trace elements in predictable ways. The factor analysis is especially successful at demonstrating shared associations, such as the increasing coaccumulation of copper, iron, and lanthanum with depth, as well as a concurrent accumulation of iron and nickel just below the South Pacific's local oxygen minimum zone.

Collectively, these techniques paint a much clearer picture of how trace metals cycle through the world's oceans and help illuminate the suite of interacting biogeochemical processes that affect multielement distributions. In the current era of burgeoning big data, these types of analyses are crucial for learning how to maximize the information that can be extracted from GEOTRACES and other large data sets. (*Global Biogeochemical Cycles,* https://doi.org/10.1029/2018GB006145, 2019) **—Terri Cook**, *Science Writer*

Chinese Swamp Core Reveals 47,000 Years of Monsoon History

Every summer, one third of the world's population receives rainfall from the East Asian monsoon. Variations in monsoon behavior can pose flood or drought risk, so understanding how it has changed over time could help clarify future risks. *Wei et al.* provide new insights into 47,000 years of East Asian monsoon history.

The new research addresses a lack of long-term, high-resolution data on past monsoon variability in southern China. To help fill this gap, the researchers collected an 8.6-meter-long sediment core from Dahu Swamp in the Nanling Mountains of southern China; the region's topography makes it particularly sensitive to shifts in monsoon rainfall patterns.

The research team took samples of material every 2 centimeters along the length of the core and analyzed each sample's magnetic properties to produce snapshots of mineral composition in the swamp at different time periods. These snapshots provided clues to the hydrologic and climatic processes in play when the materials were deposited.

Findings from the mineral-magnetic analysis enabled the scientists to reconstruct patterns of fluctuation between relatively wet and dry periods in the region over the past 47,000 years. These monsoon rainfall patterns are consistent with data from northern China and are in line with past climate changes resulting from gradual shifts in Earth's orbit and orientation.

The results also add to mounting evidence against a traditional view that climate processes at high latitudes were the primary driver of paleoclimate monsoon trends. The new findings suggest that tropical climate patterns associated with the El Niño–Southern Oscillation have played an important role in driving long-term monsoon rainfall patterns.

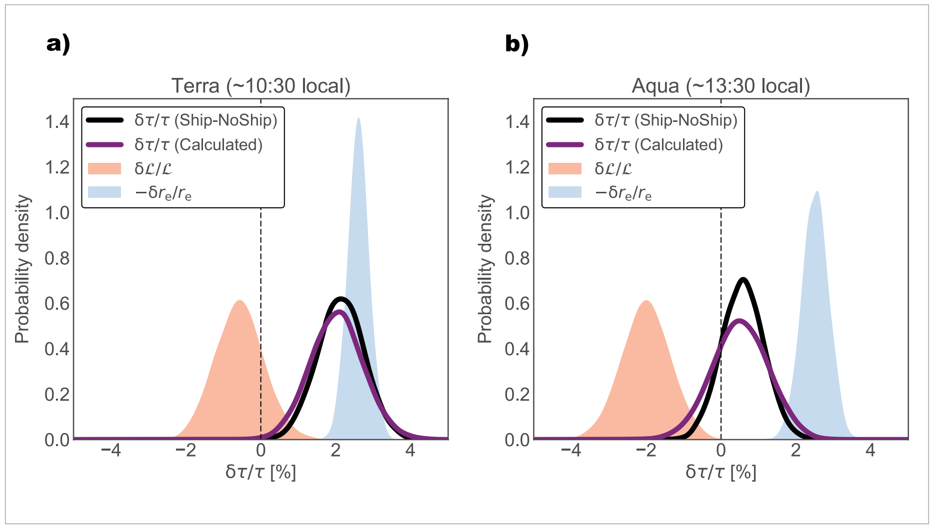
New insights into ancient trends in East Asian monsoon rainfall could help refine predictions of future flood and drought risk as global warming progresses. Credit: Kamiswlswoo, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

This research could help refine climate models and improve predictions of future shifts in monsoon rainfall patterns as climate change progresses. (*Paleoceanography and Paleoclimatology,* https://doi.org/10.1029/2019PA003796, 2020) **—Sarah Stanley,** *Science Writer*

Quantifying Aerosol Effects on Climate Using Ship Track Clouds

An influence of ships on cloud reflectivity has been evident since the dawn of satellites. Despite this, past work has not been able to robustly identify a cloud perturbation associated with large and concentrated sulfate emissions in the major shipping lanes. *Diamond et al.* [2020] take advantage of a chance alignment of winds and shipping lanes in the southeastern Atlantic Ocean to reconstruct counterfactual, ship-uninfluenced cloud fields. So doing identifies a substantial aerosol influence on the clouds and helps quantify the aerosol radiative forcing globally.

The findings not only make the case for a substantial aerosol radiative forcing from aerosol cloud interactions globally but also support a growing body of literature that contraindicates a strong effect from aerosol emissions on the amount of cloud condensate. Cloud brightening from aerosol emissions is real and substantial but not so large as some claim, and, if anything, the cloud amount moderates rather than enhances the effect. (*AGU Advances*, https://doi.org/10.1029/2019AV000111) **—Bjorn Stevens**



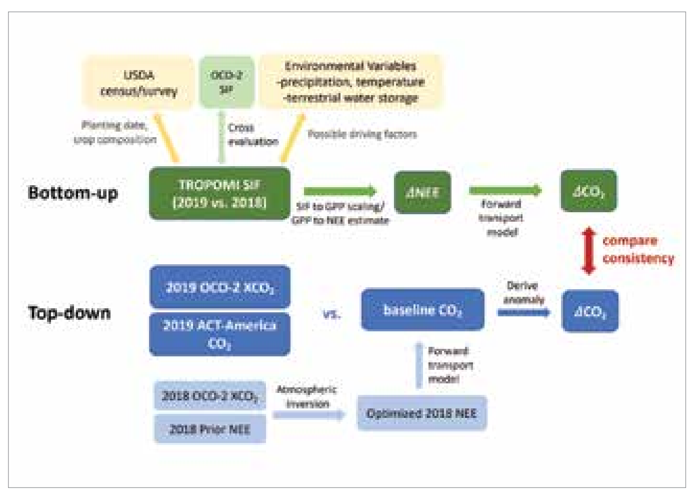
Estimates of the influence of ship emissions on cloud effective radius (blue) and cloud condensate amount (salmon) in the shipping lanes of the Southeast Atlantic. The estimates from afternoon overpasses of the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Aqua Satellite show a clear signal of opposing effects with the effective radius reduction having a positive and larger effect on cloud optical depth and hence optical properties, leading to a net enhancement of cloud albedo. Credit: Diamond et al. *[2020], Figure 3b*

Toward Forecasting Crop Productivity and Carbon Flux Anomalies

Climate change is increasing extreme weather events, such as regional flooding, which affects when farmers can plant their crops, subsequent crop productivity, and regional carbon fluxes.

For periods during and following the 2019 spring flood in the U.S. Midwest, *Yin et al.* [2020] quantified reductions in the usual patterns of crop productivity and its uptake of atmospheric carbon dioxide (CO_2) using two measurements made with satellites: (1) atmospheric CO_2 concentrations and (2) the fluorescence (re-emission of the Sun's light) by leaves of the crops. The two parameters yielded similar carbon flux estimates, thus conferring confidence in the conclusion that regional carbon uptake declined due to the flood.

Although this was a retrospective study of recent months, these satellite data are available in near real time. Further development and application of these technologies and analyses could enable improved agricultural and ecological forecasting of crop productivity and carbon fluxes, similar to current weather forecasting based on assimilation of atmospheric observations. (*AGU Advances*, https://doi.org/10.1029/2019AV000140) **—Eric Davidson**



Two independent methods were used to estimate the change in carbon dioxide (CO_2) fluxes due to widespread flooding across the U.S. Midwest region in the spring and summer of 2019. The "bottom up" method used satellite-based solar-induced chlorophyll fluorescence (SIF) data to estimate gross primary productivity (GPP) and net ecosystem exchange (NEE) of CO_2. The "top down" approach combined atmospheric models with estimates of atmospheric CO_2 concentrations from the Orbiting Carbon Observatory 2 (OCO-2) satellite. These two approaches yielded similar estimates of anomalous reduced fluxes due to the unusual flooding event. Credit: Yin et al. *[2020], Figure S*

POSITIONS AVAILABLE

Atmospheric Sciences

Howard University

Howard University invites applications for the position of Director of the NOAA Cooperative Science Center for Atmospheric Sciences and Meteorology (NCAS-M) at the rank full professor (associate professor considered). The appointment of a new director of NCAS-M is an opportunity to lead a 13-member academic and research consortium of international reputation that supports NOAA mission science in weather, climate, and atmospheric sciences. NCAS-M is the largest multi-disciplinary research program on the HU campus. This is an outstanding opportunity for a creative leader to be a part of a growing program in atmospheric and environmental sciences within the University, while supporting NOAA's vision to diversify its technical workforce.

Applications should include a cover letter, and curriculum vitae, including the names of at least three (3) professional references. The application must include separate statements of leadership, research, and teaching statements. Screening of applications will begin May 15, 2020 and continue until the position is filled. Please submit applications to the Search Committee Chair, Dr. Kim Michelle Lewis, (COAS.applications@howard.edu). To view full job announcement visit https://coas.howard.edu/college-arts-and-sciences-job-opportunities.

Established in 1867, Howard University is a federally chartered, private, doctoral/research extensive university located in Washington, D.C. The University does not discriminate on the basis of race, color, national and ethnic origin, sex, marital status, religion, or disability. Veteran status and people with disabilities are encouraged to apply. Inquiries regarding provisions for persons with disabilities, equal employment opportunity and Title IX should be directed to the Office of the Associate Vice President for Human Resources.

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks to fill a postdoctoral research associate or more senior research position for investigating the climate sensitivity and response to aerosol effects on clouds and cloud brightening with GFDL climate models and enhancing the modeling capability in aerosol and cloud microphysics, and aerosol/cloud/radiation/circulation interlinkages.

The position will focus on using the latest GFDL climate models (CM4 and ESM4) to design and execute simulations to investigate the effects of aerosol particles seeding low clouds on Earth's radiative balance, and subsequent changes in global/regional circulation patterns, hydroclimate and extreme events. Furthermore, the incumbent will improve the representation of aerosol-cloud interactions, the key process for accurately simulating and quantifying cloud brightening, by devising and implementing a scheme to track aerosol size distributions in GFDL models, and including comparisons with aerosol, cloud, radiation, and climate observations.

The ideal candidates have to demonstrate a strong background in climate modeling and climate science, as well as experience using and analyzing numerical models and/or large observational datasets.

Candidates must have a Ph.D. in atmospheric physics, dynamic meteorology, Earth system science, climate studies, or related fields. The initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding.

Complete applications, including a cover letter, CV, publication list, a statement of research interests and contact information of 3 references should be submitted online to https://www.princeton.edu/acad-positions/position/15781 by May 8, 2020 for full consideration. For more information about the research project and application process, please contact V. Ramaswamy (V.Ramaswamy@noaa.gov) or Yi Ming (Yi.Ming@noaa.gov).

This position is subject to Princeton University's background check policy.

Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Hydrology

SRNL is seeking candidates to participate in the ongoing development of a surface water modeling program in support of Department of Energy and other U. S. Government agencies with interests in national security, international nuclear non-proliferation and emergency response.

The successful candidate will be expected to engage in research, development and application of state of the science surface water models simulating two and three dimensional flows and the resulting transport and dispersion of contaminants released into those water systems. Particular focus will be on DOE funded projects to develop modeling technologies supporting responses to incidents of national significance involving the unexpected release of hazardous contaminants into U. S. waterways. Resources include advanced models developed at SRNL, as well as EPA and the U.S. Corps of Engineers. Applicable modeling scales range from streams and rivers to dynamically driven lakes, bays and tidally forced coastal estuaries. Additional duties may include modeling of flood impacts following extreme rain events or dam break scenarios.

The candidate must possess excellent written and oral communications skills, willing to present work at professional conferences and government forums, and comfortable advocating for the water modeling program among SRNL organizations and U. S. government sponsored.

EPFL

Faculty positions in Architectural Design and Architecture and Digital Processes

at the Ecole polytechnique fédérale de Lausanne (EPFL)

EPFL's School of Architecture, Civil and Environmental Engineering (ENAC) invites applications for two faculty positions in Architecture. The positions are open at the levels of Tenure Track Assistant Professor, Associate Professor or Full Professor.

The Institute of Architecture and the City (IA) is hiring Professors in the areas of **Architectural Design** and **Architecture and Digital Processes** to address the systemic challenges posed by the continued climate crisis, rapid urbanization, and the threat of collapsing eco-systems. Architecture and urban/territorial design must acquire an insightful understanding of their mission as transformed and transforming disciplines with the ability and responsibility to bring up progressive and inclusive visions and solutions for our present, operating as catalysts within the ecological transition that is vital for life on earth. IA being part of a science and technology research university provides a pointed potential to engage further Architecture's disciplinary capacities in design and synthesis.

Architectural Design: We intend to engage with Architecture beyond the conception of a single or a multitude of objects, to approach the architectural project in a trans-scalar mode based on an understanding of the built and non-built environment as a whole and architectural articulation as an emergent outcome of the complex correlation of ecological systems and humans. These notions demand us to revisit our traditional disciplinary focus on singular authorship of individual persons towards a collective and shared endeavor. The appointee will be an architect recognized internationally.

Architecture and Digital Processes: We plan to push the frontiers of translational capacities of digital processes between disciplines and domains. The appointee will work on large datasets and diverse digital tools in a trans-scalar way and be keenly interested in both analytical and holistic modes of operation in research and design. S/he should have an innovative and forward-looking agenda with a key focus on the interactions of the natural and built environments with the digital. The work associated with this position will focus on the epistemological consideration and translation of information into architectural instruments, design and projects.

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

The following documents are requested in PDF format: cover letter including a statement of motivation, curriculum vitae, publications list, concise statements of research and teaching interests (3-5 pages) as well as the names and addresses, including emails, of at least three references for junior candidates, five for senior candidates (they may be contacted at a later stage). Applications should be uploaded to the EPFL recruitment web site:

https://facultyrecruiting.epfl.ch/position/21823490

Formal evaluation of the applications will begin on **15 June 2020**.

Further enquiries should be made to the Chair of the Search Committee:
Professor Claudia R. Binder
Dean of ENAC
E-mail: ArchiDesignArchiDigi@epfl.ch

For additional information on EPFL, please consult: epfl.ch or enac.epfl.ch

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

Leibniz-Institut für Ostseeforschung Warnemünde IOW

Universität Rostock Traditio et Innovatio

At the Leibniz Institute for Baltic Sea Research – Warnemuende (IOW) the position of the

Director

is available from 1st October 2021.

The IOW is a member of the Leibniz Association (WGL e.V.). With its four scientific departments Physical Oceanography and Instrumentation, Marine Chemistry, Biological Oceanography and Marine Geology, it conducts basic marine research within the framework of a multi-year research programme. The focus is on coastal, marginal and shelf seas with a special focus on the Baltic Sea. Through an administrative agreement with the Federal Maritime and Hydrographic Agency, the IOW is charged with the tasks of environmental monitoring of the Baltic Sea within the framework of HELCOM.

The position of the director encompasses also a

W3 professorship for Earth Systems Analysis

at the University of Rostock.

IOW and the University of Rostock invite applications of outstanding scientists in earth system analysis – preferably in marine science. Experiences in leadership, science administration and management are required. The Director is responsible for the scientific management of the IOW and for representing the Institute externally and internally. In particular, impulses for research design and structures and the lead in the program budget of the IOW as well as constructive cooperation in the profile line Maritime Systems of the Interdisciplinary Faculty of the University of Rostock are expected. The teaching obligation is 2 credit hours.

For further inquiries, please contact:

Prof. Dr. Detlef Schulz-Bull, chair of appointments committee
Telefon: +49 381 5197 310
e-mail: **detlef.schulz-bull@io-warnemuende.de**

Qualifications are as per § 58 of the Higher Education Act of the State of Mecklenburg-Vorpommern (LHG M-V). Details will be explained on request.

Please direct your application with the usual documents *** no later than 5 June 2020*** preferably by e-mail to:

dekan.mnf@uni-rostock.de or to

University of Rostock
Dean of the Faculty of Mathematics and Natural Sciences
Wismarsche Straße 45
18057 Rostock

For the full announcement, please consult the internet at:
www.uni-rostock.de/stellen/professuren

Greetings, All!

I'm Michelle Lee from Lamont-Doherty Earth Observatory at Columbia University.

In this photo, Dr. Alistair Harding (left) and I are taking apart and labeling "birds" from seismic streamers while aboard the R/V *Marcus Langseth* for the Axial3D expedition. (Streamers are buoyant, ship-towed cables that connect hydrophones; birds are devices that get attached to streamers to keep track of GPS location and control streamer depth in the ocean.) Throughout the cruise, different situations can prompt the need to bring the streamers on deck and then later deploy them back into the ocean.

Our goal is to successfully acquire the marine seismic data needed to image the magmatic structure beneath Axial Seamount. To prepare the birds for the next deployment, they need to be removed from the streamer, taken apart, and put back on the shelf in the correct order. While it's not always easy to know when the streamers need to be retrieved and then redeployed, the scientific party and the marine techs work together to ensure that the streamer retrievals and deployments run efficiently and smoothly.

—Michelle Lee, Graduate Student, Lamont-Doherty Earth Observatory, Palisades, N.Y.

View more postcards at bit.ly/Eos-postcard