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Eos

EARTH & SPACE SCIENCE NEWS

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The Road Ahead…

All year in the pages of *Eos,* we've been celebrating 100 years of science since AGU's founding in 1919. Each month we focused on a broad theme—from studies of Earth's interior to the atmospheres of other planets—though in no way could we truly encompass the breadth and depth of work our members conduct across the Earth and space sciences.

Throughout AGU, we embarked on a massive yearlong initiative to mark our centenary. On page 40, you'll see what AGU and its membership were able to accomplish. More than 3,000 of you donated to support the next generation of scientists through the Austin Student Travel Grant Challenge (and it's not too late to become a donor at agu.org/Austin). By the end of the year, nearly 100 papers will have been published across AGU journals tackling science's next Grand Challenges. AGU launched its Ethics and Equity Center and cut the ribbon on our net-zero energy headquarters in Washington, D.C., allowing us to lead by demonstration of our values.

This work doesn't end with our anniversary. As AGU embarks on its second century, we created this issue of *Eos* as a proper look forward to our future. What challenges—like dealing with big data (p. 16)—will science face? What novel ideas—like community science (p. 36)—will catalyze our work for the benefit of humanity? And through all these questions, how can AGU best support our network of scientists so that we can figure this all out together?

As we face the future, let's not forget what brought us all here in the first place: the passion for discovery. We honor that passion with our special Centennial cover artwork. The issue you're holding has one of 10 unique covers, each focusing on a theme we highlighted this year. Together (see below) they honor our 100th year and will be featured in displays at our Fall Meeting in San Francisco this month. Inside, you'll find the full poster by artist Ellen Schofield, and we hope you enjoy searching through it for the hidden gems we included to represent each of your fields. (Think you found them all? Flip it over to find the annotated version.)

Finally, we want to offer special thanks to our Science Advisers, whose names are listed on the masthead to the right. *Eos* has evolved significantly over this Centennial year, and the publication's continued success is due to their support and expertise, along with that of our hardworking writing, editing, and production staff. We look forward to producing *Eos* in deeper partnership with our advisers to bring you the most interesting and important science from our community in the next 100 years.

See you next century!

Heather Goss, Editor in Chief

These 10 covers celebrate the Centennial themes Eos *has covered this year. Across the top row: Science policy and education; cryosphere sciences; Earth deep interior to surface studies; atmospheric sciences; and space and planetary sciences. On the bottom row: Climate sciences; ocean sciences; paleoceanography and paleoclimatology; planetary processes; and natural hazards. Artist: Ellen Schofield (ellenschofield.com)*

Eos

AGU100 ADVANCING EARTH AND SPACE SCIENCE

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Christine W. McEntee, Executive Director/CEO

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Illustration by Ellen Schofield (ellenschofield.com)

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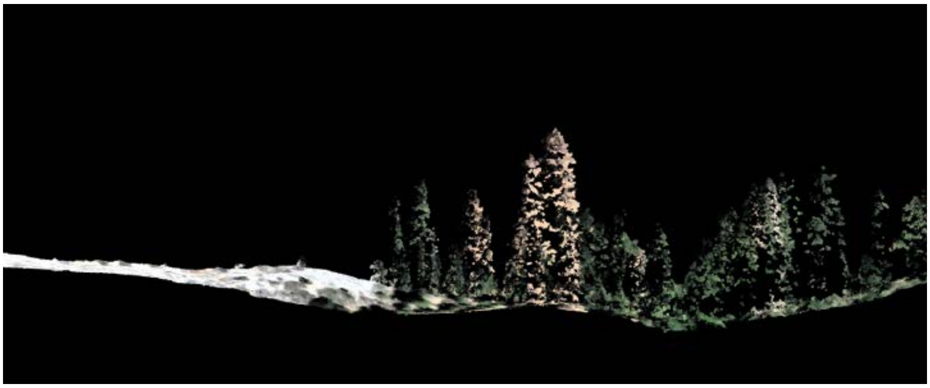
The Bigger They Are, the Harder They Fall



A view of trees imaged using lidar. Using this technology, researchers tracked the health of individual trees over a 40,000-hectare area. Credit: Atticus Stovall

Every year, millions of people flock to see the giant trees in California's Sequoia and Kings Canyon National Parks and Redwood National and State Parks.

"It's just emblematic of what people value. People value big old trees," said Nate McDowell, an Earth scientist at the Pacific Northwest National Laboratory in Richland, Wash.

Unfortunately, climate change puts these large trees at increased risk. "In the future, we might see droughts become more severe and more frequent," said Xi Yang, an environmental scientist at the University of Virginia in Charlottesville.

Yang was the senior researcher on a study recently published in *Nature Communications* reporting that taller trees died at more than twice the rate of smaller trees at the end of extreme drought (bit.ly/tall-trees). "Of the trees above 30 meters tall, nearly half of them died during this study, which is a staggering number," said lead researcher Atticus Stovall.

Tracking a Tree's Death from the Air

The researchers were able to track the mortality of 1.8 million trees in California from 2009 to 2016 in an area spanning over 40,000 hectares—roughly the size of Denver—using lidar measurements taken from an aircraft.

From an airplane cruising at 1,000 meters, lidar has a vertical resolution on the order of centimeters, Stovall said. "You can see birds in lidar data sets, which is really crazy."

With this level of granularity, researchers could identify individual trees and assess mortality across the landscape. "There's no two same trees in the world," Yang said.

"Something I feel is really important for the public to understand is that things aren't going to get better. In their lifetimes, things won't get better. Things will only get worse, especially for big trees."

Being able to track individual trees is important for understanding what biological or environmental factors drive their functioning. "This, to my knowledge, is the first study that has taken individual tree mapping and linked it with trends in mortality like this," Stovall said.

Using lidar allowed researchers to survey a much larger landscape than previous studies, said McDowell, who was not involved with the study. Traditionally, scientists on the ground would survey plots of forest to monitor tree health. Although these plot measurements are robust, they miss the entirety of the forest for all the trees in it.

Case in point: Only about 17 trees were taller than 70 meters in the entire data set. "Statistically speaking, you would almost never find those trees in that 40,000 hectares," Stovall said. "If you found one of those trees, it would be like you hit the jackpot."

Bad News for Big Trees

Although tree height was the strongest predictor of tree mortality, environmental factors like water and competition also played a role. Another primary risk factor was the vapor pressure deficit (VPD). The higher the VPD, which is associated with higher temperatures and lower humidity, the more prone trees are to drying out and dying.

Large trees died at even higher rates when the VPD was high. "In a way, a lot of it is physics," Stovall said. The tree's xylem is like a straw, he said, and large trees require larger straws to move more water from roots to the leaves. The stress of a drought likely makes these trees more susceptible to cavitation, "which is literally a column of water within that straw being ripped apart," said Stovall. The air bubble that forms in the water column "renders the entire water transport system useless—it's pretty dramatic."

For McDowell, the data showing the role VPD played in tree mortality were particularly striking. "Something I feel is really important for the public to understand is that things aren't going to get better," he said. "In their lifetimes, things won't get better. Things will only get worse, especially for big trees."

And what is bad for large trees is bad for the environment as a whole.

"They hold and filter tons of water," Stovall said. "They're literally sequestering carbon, so they're helping us out there, too."

McDowell agreed: "It's the big old trees that store the most carbon. And we need that to mitigate climate warming." Loss of these large trees would likely exacerbate the effects of global climate emissions.

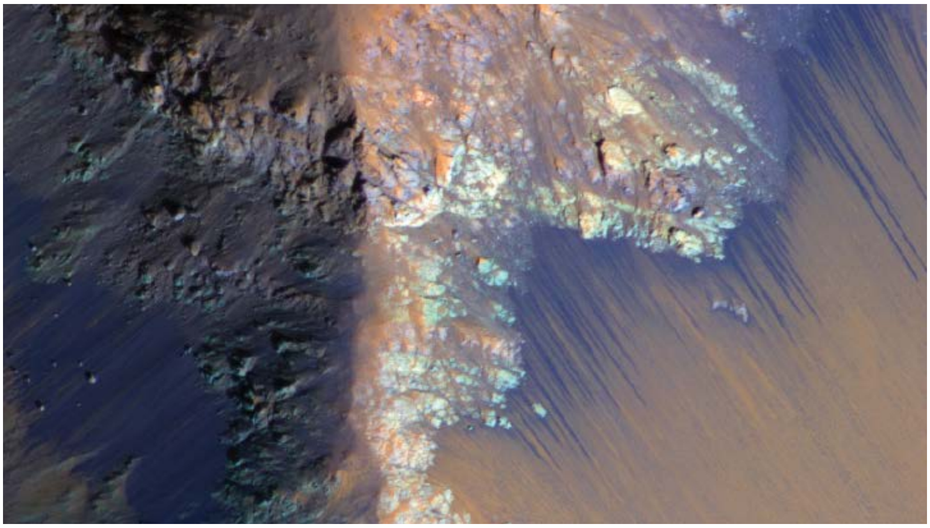
There are short-term management strategies for preserving large trees, like clearing smaller trees to reduce competition for water, but "they're a Band-Aid; they're not a cure," McDowell said.

In the end, saving the large trees "comes down to the hard things that everyone is well aware of," Stovall said.

"I don't want to tell people how to live their lives," Stovall continued. "But the science here is really pointing toward this reality that the decisions that everyday people make in terms of emissions and carbon footprint and everything really do have large-scale effects on the environment."

By **Richard J. Sima** (@richardsima), Science Writer

Protecting Potential Life at the Cost of Exploration

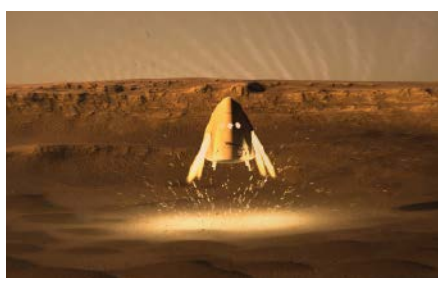


Recurring slope lineae on Mars, like these dark streaks seen by the Mars Reconnaissance Orbiter, were thought to be caused by actively seeping water. More recent research suggests that liquids have a very minor role in their formation. Credit: NASA/JPL-Caltech/University of Arizona

"Our guidelines on how we protect the places we're going from contamination and how we protect our own planet on the way back are in urgent need of updating," Thomas Zurbuchen, the head of NASA's Science Mission Directorate, told reporters at an October press conference. Those guidelines for planetary protection must be updated, streamlined, and uniformly implemented across the agency and the private sector, according to a new report (bit.ly/potential-life).

NASA convened the Planetary Protection Independent Review Board (PPIRB) earlier this year to address concerns about its planetary protection guidelines. Past reviews found that the protocols are based on Apollo-era science and technology, are unevenly applied to exploration missions, can be a significant burden to low-budget missions, and fail to address the private sector of the spaceflight industry.

The PPIRB's 18 October report "really addresses both our changing knowledge of other worlds in our solar system and the changing landscape of space exploration itself," said Lucianne Walkowicz, an astronomer at the Adler Planetarium in Chicago who was not involved with the report. "This report is a great first step in reassessing what we think we know, so we determine a better path forward."



A commercially built capsule, the SpaceX Dragon, lands on Mars in this artist's rendering. Credit: Kevin Gill, CC BY 2.0 (bit.ly/ccby2-0)

Being Realistic About Risk

Since the 1960s, international space policy has considered the entirety of a world to have a singular potential to develop life or to have foreign life catch on. But now, "we have a much more nuanced, and for that matter, sophisticated, view," said Alan Stern, who led the PPIRB and is a planetary scientist at the Southwest Research Institute in Boulder, Colo.

"While some places on Mars have high interest for understanding the potential for past life on Mars or even prebiotic development of life, not all places on Mars have that potential," Stern said.

On the basis of discoveries like that, the PPIRB report recommends that after more study, some regions of the Moon and Mars might be recategorized to a lower protection level. Doing so would significantly lower the cost burden on missions targeting the "unsuitable" areas, the board concluded.

"If space policy is not informed by scientific advancement, then it will put undue pressures on space exploration," said Edgard Rivera-Valentín, who was not involved with the report. They are a planetary scientist at the Universities Space Research Association and the Lunar and Planetary Institute in Houston.

Walkowicz had mixed feelings. "On the one hand, having region-specific planetary protection ratings acknowledges that different environments exist on any given body and is more in keeping with what we know about these worlds. I'm a bit concerned, though, about the level of deep knowledge needed to do something like that."

For example, she said, it may not make sense to categorize subsurface regions on Mars on the basis of surface features. "I think there's still a lot of room for error, which worries me when I think about the potential cost to Mars, particularly as a site of astrobiological interest," she said.

Tardigrade Stowaways

Private spaceflight initiatives should hold to the same planetary protection standards as NASA, but those policies should not stymie commercial progress, the board recommended.

"As NASA prepares for more frequent missions...through commercial partnerships, it is important that the U.S. government's policies enable these missions," Tommy Sanford, executive director of the Commercial Spaceflight Federation in Washington, D.C., told reporters.

The report also calls for transparency and accountability from commercial companies should something go wrong. The review board highlighted the Beresheet lander developed by SpaceIL that crashed on the Moon earlier this year. It was later discovered that an undisclosed cache of DNA samples and tardigrades was on board. Although including them was not illegal, the lack of transparency concerned many in the planetary protection community.

The report recommends enacting sanctions against bad actors and holding the people who provide a payload, rather than those who launch it, accountable.

NASA's upcoming Dragonfly mission (artist impression) will land on the surface of Saturn's moon Titan, which has a subsurface liquid water ocean. Credit: NASA

However, "I believe sanctions are only an effective method up to a certain point, specifically, a certain profit margin," said Monica Vidaurri, an astrobiologist and policy and ethics specialist. Vidaurri is consulting for NASA Goddard Space Flight Center in Greenbelt, Md., and was not involved with the report. The report is a "great start," she said, but the policy will need to be explicit in how sanctions would work "rather than just a broad intent of meeting breaches with sanctions."

"I believe the next steps are for the space community to begin to come to terms with and have the difficult discussion surrounding who the main actors are in space and whether the goals they have are inherently globally just," Vidaurri said.

Customizing Ocean Moons

The PPIRB recommended extensive study of the ways in which ocean worlds transport material from their icy surface to the subsurface ocean before spacecraft attempt to land. NASA has two upcoming missions to ocean worlds: Dragonfly to Titan and Europa Clipper to Europa.

"We just need to sit down and really talk about these worlds and what the transport mechanisms are and how viable terrestrial microorganisms might be in their oceans," said PPIRB member Amanda Hendrix of the Planetary Science Institute in Lakewood, Colo. It's possible that each ocean world will need a separate treatment under the new planetary protection standards, the board said.

"A lot of the report mentions that the likelihood that organisms can survive in various interesting planetary environments, like Mars [and] the subsurface of Europa, is very small," Walkowicz said. "While I applaud the planetary science community's efforts to carry out studies to determine whether that statement is true, I am also concerned that we don't yet know that it is true. I think a lot about the cost of being wrong, what is or may be lost."

"To ensure proper care when we visit bodies beyond Earth, space policy needs to keep up."

"I think there are some exciting opportunities for people to think creatively, not only about how we clean our spacecraft but even about how we choose materials to construct them that might better enable missions to meet planetary protection requirements," she said.

Dealing with Human Contamination

"This is a really timely report because our nation is preparing to return humans to the Moon with the hopes of this time those first steps being a giant leap toward Mars," Rivera-Valentín said.

Human space exploration will be messy, the board concluded, and humans will inevitably contaminate any environment by living there for an extended time. "I strongly agree with the PPIRB that planetary protection planning for human missions is immature and that the current planetary protection rating for Mars precludes human missions," Walkowicz said.

Will astrobiology missions still be viable in places with human explorers nearby? The review board recommends finding out ahead of time whether the two mission types should be segregated.

"I am glad to see the attention...on determining how astrobiological investigations can be carried out with human involvement," Walkowicz said. "It's particularly smart to think about these missions as extensions of the exploration of sensitive analogue environments here on Earth like the Atacama or Antarctica, as I suspect there are lessons we can learn there."

Implement Early and Update Often

NASA should set the planetary protection standards for a mission early in the mission's planning and development phases to keep costs down, the review board recommended. "Not only is it cost-effective," Vidaurri said, "but [it] helps establish these practices as custom, which is absolutely crucial since the review calls on communicating new planetary protection approaches to the United Nations that other nations will then be encouraged to employ."

NASA's planetary protection policies have not substantially changed in 50 years. The report recommends that going forward, NASA examine and update its policies at least twice a decade and establish a forum for ongoing discussion.

"Planetary science and astrobiology are fast growing fields because they are exploration science, as in they are constantly being motivated by new observations and discoveries rather than by hypotheses," Rivera-Valentín said. "To ensure proper care when we visit bodies beyond Earth, space policy needs to keep up."

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

Making Citizen Science Ethical

It's common for consumers to wonder how social media sites use their data or what methods banks use to protect their financial information online. But what about data collected for citizen science projects?

On the surface, participating in citizen science projects can seem like an innocuous way for interested individuals, even children, to have fun, experience science enrichment, and meaningfully contribute to research. Such projects don't appear to be cyberspace lurking spots where data predators lie in wait to commit nefarious acts. Yet if care isn't taken, real harms can occur to citizen scientists, researchers note in "Coercion, Consent, and Participation in Citizen Science," a study posted to arXiv (bit.ly/cit-science).

The paper discusses ethical questions, issues, and considerations surrounding citizen science projects. The research has been accepted for publication in *Science and Engineering Ethics,* said Pamela Gay, a senior scientist at the Planetary Science Institute in Tucson, Ariz., and a coauthor of the paper. Alison Reiheld, a philosopher studying ethics issues at Southern Illinois University in Edwardsville, is the other coauthor.

Is This Citizen Science or a Game?

Gay said that the idea for the project was sparked by the results of user design testing conducted with first-time citizen scientists for an online CosmoQuest project. CosmoQuest is an online platform connecting citizen scientists with NASA projects to help map the surface of rocky bodies in our solar system and explore the atmospheres of celestial bodies across the universe. The original goal was to evaluate whether the website design made sense to new citizen scientists and conveyed the information needed for them to be able to accomplish scientific tasks for the project, she said.

Part of this process entailed asking users how they thought data collected through the website would be used. Even though the website was designed to align with the best practices of the time and included such statements as "You are contributing data to help NASA," some citizen scientists misunderstood the intended uses for project data, Gay said. Many participants said they thought the project tasks were part of a game or training exercise and didn't realize the collected data were intended for research.

This confusion left Gay wondering, How often have citizen scientists misunderstood

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the nature of the projects in which they have participated? How often have they not realized their data were being collected and used for research purposes?

Informed Consent and Ethical Citizen Science

In the paper, Gay and Reiheld make it clear that ethical citizen science research must ensure that participants have given truly informed consent.

One piece of this puzzle requires providing digestible information detailing what participant data will be collected, how they will be used, and the potential impacts of those uses. For instance, participants in some studies may not realize that in addition to the research use of data they submit, they may be agreeing to the use of their demographic data in future studies assessing certain characteristics of people who take part in citizen science, Gay said.

In addition, Gay and Reiheld maintain, researchers must explain to prospective citizen scientists what, if any, formal recognition they might receive for their efforts. For instance, will their name be listed on the project website? Will they be named as coauthors on studies that are published? The team also said that scientists need to explain how their own careers might benefit from the citizen science project (such as receiving awards, funding, promotions, or tenure).

The use of easy-to-understand documents with minimal text can help ensure informed consent, the team noted, especially when contributors might not be fluent in the same language as the researchers. For online projects, to ensure participants have agreed to the project terms, log-ins must be used, Gay said.

Another critical component to ethical citizen science research is ensuring that participants can provide uncoerced consent to the terms of the project.

If children are too young to provide consent to, say, having social media accounts or other online uses of their data, they also can't consent to having their data collected through online citizen science projects, Gay said. Moreover, she said, using data from child citizen scientists can create harm if their main takeaway from the exchange is that adults benefited from using their information but the children didn't gain much in return. This perception of imbalance can be particularly damaging if it happens when children don't have much experience with science; it can potentially encourage them to become science averse, Gay added.

Instructors and others interested in helping youngsters learn more about citizen science can use alternative means, such as discussing the field using citizen science or showing examples of projects without actually submitting data to them, Gay said.

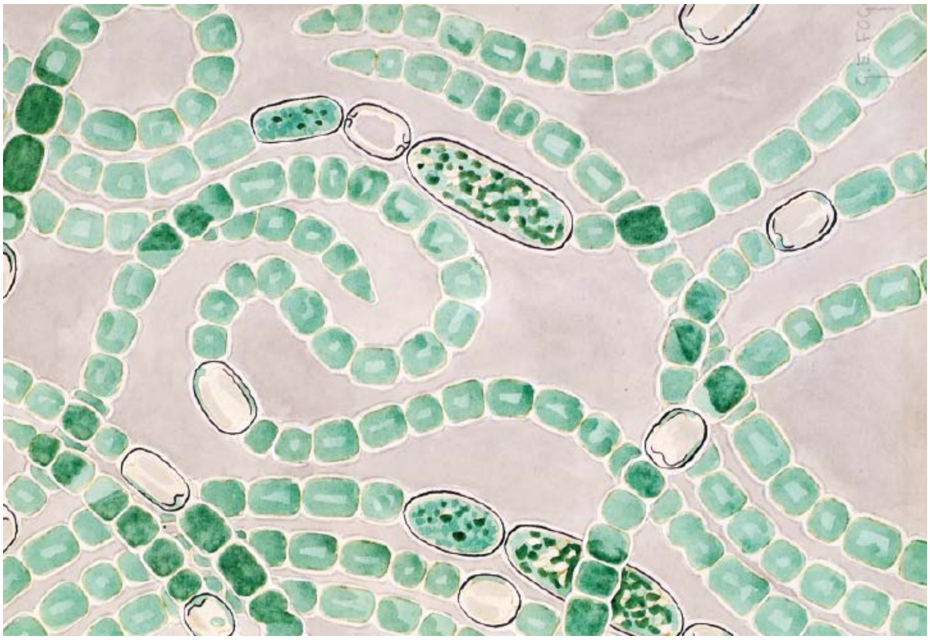
Researchers found that older children and even adults can be coerced into citizen science project participation. Often the coercion is accidental. An egregious example is when instructors require project participation for a classroom grade and don't offer any alternative means for earning credit for the assignment, Gay noted. Even offering citizen science projects as one of several possible ways of earning a grade can be coercive because that project might seem easier or less time-consuming than the alternatives, she said.

"This project challenges us to think about the many relevant paradigms that might inform judgments about ethical obligations in citizen science," said Ana Iltis, director of the Center for Bioethics, Health and Society at Wake Forest University in Winston-Salem, N.C. Iltis was not involved with the study.

"For example, collecting and using data about citizen scientists for research on citizen science might be more like doing an observational study or using patient records to do research than enrolling patients into a randomized clinical trial. There are possible paradigms beyond what we typically see as human research and health care, such as marketing research in which virtually all of us unwittingly participate when we shop online or go to the grocery store. Looking at the questions citizen science raises might encourage us to rethink some existing entrenched paradigms," Iltis added.

By **Rachel Crowell** (@writesRCrowell), Science Writer

Did Bacterial Enzymes Cap the Oxygen in Early Earth's Atmosphere?



Nitrogenase, an enzyme produced by cyanobacteria like these, may have sustained Earth's low-oxygen "Boring Billion." Credit: Anabaena cylindrica, *a filamentous cyanobacterium, 1946 watercolor by G. E. Fogg, FRS*

Oxygen is essential for life on Earth, but this was not always the case. Before about 2.4 billion years ago, Earth was a virtually oxygen-free environment. The appearance of cyanobacteria, or blue-green algae, changed all that.

Cyanobacteria injected the atmosphere with oxygen, setting the scene for the development of complex life as we know it. But a funny thing happened: Although conditions were ripe for algae to pump more oxygen into the atmosphere, oxygen levels remained low. And they stayed low for the next 2 billion years.

Researchers have proposed many theories to explain the oxygen lag, including a lack of nutrients for the cyanobacteria or limited supplies of nitrogen. But the exact mechanism that kept oxygen production low remains a mystery.

In a new paper in *Trends in Plant Science,* scientists suggest that an enzyme contained only in cyanobacteria may have acted as a regulator of oxygen for billions of years (bit.ly/oxygen-enzyme). The enzyme may have essentially capped the amount of oxygen produced by the algae until the evolution of complex plants overrode its limits about 450 million years ago.

The Origins of Oxygen

Until about 2.4 billion years ago, bacteria lived in an environment with no oxygen. To photosynthesize, they used electrons from hydrogen sulfide, hydrogen, or iron to trigger photosynthesis.

But around that time, "the cyanobacteria really discovered something that changed everything," said John Allen, a biochemist at University College London. They "invented a brilliant new way of doing photosynthesis, which was to take electrons from water," he explained.

The by-product of photosynthesis is oxygen, and the new gas accumulated in the atmosphere. This event, called the Great Oxidation Event, marked the end of the Archean.

Although cyanobacteria cracked the photosynthesis code and introduced oxygen to the atmosphere, atmospheric oxygen levels were stagnant and rose to only about 10% of our present-day levels.

Those low levels persisted for almost 2 billion years, even though blue-green algae had everything they needed to thrive, said Allen. "They should be unstoppable, because water is everywhere," he added.

What Held Oxygen Back?

Researchers have long been trying to uncover why the oxygen levels stayed low. Some scientists think that the availability of metals in early Earth limited oxygen-producing cyanobacteria.

But Allen was unconvinced.

"These trace metals act like lubricants," he said. "They're not being used for fuel." He compares trace metals to the oil in a car—it just lubricates the engine, whereas gasoline actually powers the car. Allen and his colleagues were looking for a model that had a simpler solution with a feedback mechanism.

Coauthor Brenda Thake, of Queen Mary University of London, noted that when cyanobacteria are grown in laboratory conditions in which light and trace elements abound but combined nitrogen is limited, the cyanobacteria fix their own nitrogen by using an enzyme called nitrogenase.

The cyanobacteria photosynthesize and produce oxygen, explained Allen, but the oxygen feeds back into the system to inhibit the enzyme nitrogenase. He pointed out that the process is like a thermostat telling a heater to shut off instead of heating a room indefinitely.

The result is that lab-grown cyanobacteria will produce oxygen but to no more than 10% of our present levels—exactly the amount of oxygen produced in the Proterozoic.

"I think the Boring Billion, under the surface, was not at all boring. There were all sorts of very interesting things going on in this world of very low oxygen concentration."

Allen said, "This was too much of a coincidence to be a coincidence." He noted that the team thought the very low oxygen levels "could simply be that the oxygen being produced inhibited nitrogenase, which prevented cell growth."

Their hypothesis is an interesting one, said Christopher Junium, a stable isotope geochemist at Syracuse University in New York. He was not involved with the study.

"I think what's key is that they present a broadly testable hypothesis" about why oxygen was limited after the Great Oxidation Event, said Junium. He said that this study focuses on one particular organism, but there's room for scientists to test other cyanobacteria to see how they respond in a laboratory setting.

Junium also noted that the organic microfossil record is pretty limited. But expanded investigations might shed light on the evolutionary process even more. "Just because we've only found heterocysts from 408 million years ago and younger doesn't mean that they don't exist in deeper time," said Junium.

After the Oxygen

After the first appearance of oxygen, there's quite a stretch of time when oxygen levels stayed the same—what scientists have dubbed the "Boring Billion." But Allen takes umbrage with that term.

"I think the Boring Billion, under the surface, was not at all boring," Allen said. "There were all sorts of very interesting things going on in this world of very low oxygen concentration."

He explained that complex, multicellular organisms evolved, eventually dying and accumulating in organic-rich deposits. Allen says plants' becoming firmly rooted on land allowed for the evolution of a physical separation between aerial oxygen and nitrogen fixing in soil.

"The bigger apparent increase in oxygen content really does coincide with the evolution of land plants," Junium said. He added that there was a "pretty broad range of evidence" that atmospheric oxygen levels rose during this time.

The connection between plants and oxygen makes sense, said Junium. "The consequence of carbon burial, when it's produced by oxygenic photosynthetic organisms like vascular plants (Devonian ferns, for example), is increasing oxygen."

The new paper will generate a lot of scientific discussions, said Junium. A theory-focused paper is a rarity these days, but he added that "it was neat—I feel like there should be more papers written like this."

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

Humans Releasing More Deep Carbon Than Volcanoes, Asteroids

A researcher collects gas at Lastarria volcano in northern Chile. Credit: Yves Moussallam, Lamont-Doherty Earth Observatory

Of the 1.85 billion billion metric tons of carbon on Earth, 99.8% exists belowground, according to new reports on deep carbon.

The research estimates that human activity annually releases into the atmosphere around 40–100 times as much carbon dioxide as does all volcanic activity. That's also a slightly higher rate of carbon emission than Earth experienced just after the asteroid impact that likely killed the dinosaurs, the researchers found.

Carbon "provides the chemical foundation for life...and it plays a disproportionate role in Earth's uncertain, changeable climate and environment," Deep Carbon Observatory (DCO) executive director Robert Hazen said in a statement in October. Scientists with DCO led the studies on Earth's carbon, which were published in *Elements* (bit.ly/deep-carbon).

"We cannot understand carbon in Earth—we cannot place the changeable surface world in context—without the necessary baseline provided by deep carbon research," Hazen said.

A Mostly Steady State

The new reports summarize 10 years of field data collection, lab experiments, and computer modeling of the origin of Earth's carbon, how it circulates throughout the Earth system, and extreme events that can upset Earth's carbon balance. The research estimates that Earth holds a total of 1.85 billion gigatons of carbon, although estimates of total carbon content of the core and lower mantle are speculative and likely to change with future research.

99.8% of Earth's 1.85 billion billion metric tons of carbon exists belowground.

"It's almost like a forensic detective story, putting together lots of bits of evidence using a wide range of techniques to come up with a planetary carbon budget," DCO volcanologist Marie Edmonds of the University of Cambridge in the United Kingdom said at an October press conference.

More than 90% of the carbon that exists above the crust resides in the deep ocean and in marine sediments. The atmosphere contains only 1.4% of all above-surface carbon, mostly in the form of gaseous carbon dioxide (CO_2).

With few exceptions over the past 500 million years, Earth has maintained a balanced carbon cycle, returning to the ground about as much carbon as it outgasses. Silicate weathering is the fastest way to return carbon belowground, with smaller contributions from organic carbon burial, ocean crust update, and subduction (see Figure 1a).

In the past 500 million years, four volcanic eruptions created large igneous provinces (LIPs) that each released massive quantities of CO_2 over tens of thousands of years. These LIPs caused the aboveground quantity of CO_2 to spike to about 170% of its steady state value, which led to warmer surface conditions, more acidic oceans, and mass extinctions.

Likewise, large impact events, including the Chicxulub impact 65 million years ago, released large quantities of carbon from the subsurface into the atmosphere.

"The Chicxulub event…greatly disrupted the budget of climate-active gases in the atmosphere, leading to short-term abrupt cooling and medium-term strong warming," DCO scientists Balz Kamber and Joseph Petrus said in a joint statement.

Humans emit CO_2 into the atmosphere at more than 10 times the rate at which natural geologic processes return it belowground.

The Volcanic Details

Volcanic regions—including fractures, faults, soil, lakes, mid-ocean ridges, and active vents—outgas 280–360 million metric tons of CO_2 per year through direct venting and diffuse emissions. In a steady state carbon cycle, this is the largest contributor to aboveground carbon. Other varied geologic processes outgas an additional 20–40 million metric tons of CO_2. Widespread regions like Yellowstone, the East African Rift, and China's Tengchong volcanic field can also have significant diffuse CO_2 emissions.

"We have achieved a much more complete picture of volcanic carbon dioxide degassing on Earth, reinforcing the importance of active volcanoes," said U.S. Geological Survey geologist Cynthia Werner. The degassing studies also led to the discovery that hydrothermal provinces and areas of continental rifting are also dominant regions of planetary outgassing."

Continuously monitoring outgassing rates and compositions could also serve as a new eruption forecasting tool. At seven active volcanoes—including Italy's Etna and Stromboli and the United States' Kīlauea and Redoubt—the ratio of CO_2 to sulfur dioxide changed significantly months or years prior to large eruptions, according to these studies. In some cases, the outgassing change happened before precursor quakes and ground deformation.

Humanity's Outsized Carbon Impact

By far the largest disruptor of Earth's steady state carbon cycle is anthropogenic outgassing. The new reports indicate that humans emit around 10 gigatons of CO_2 into the atmosphere each year (see Figure 1b). That flux is more than 10 times the rate at which natural geologic processes return it belowground, according to the studies.

The rate of anthropogenic carbon emissions is higher than that from extinction-level impacts and large outpourings of magma and is 40–100 times higher than the emission rate from all natural outgassing phenomena. Researchers noted that Earth is responding to human emissions with all the hallmarks of massive carbon perturbation of the past: hotter surface temperatures, disruptions to the hydrologic cycle, ocean hypoxia and acidification, and mass extinction.

"To secure a sustainable future, it is of utmost importance that we understand Earth's entire carbon cycle," Edmonds said in a statement. She added in the press conference, "Earth will rebalance itself, but it will take 100,000 years."

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

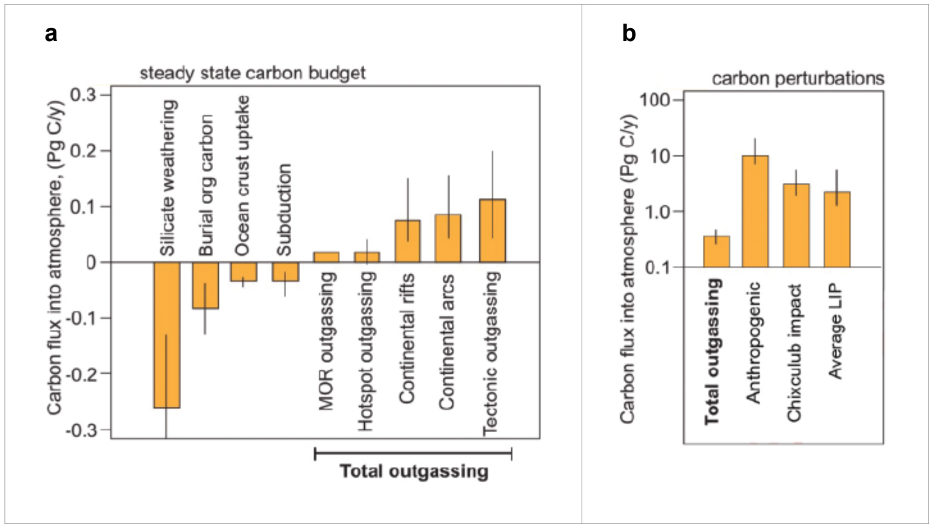


Fig. 1. (a) The annual rate of carbon exchange with the atmosphere from geologic ingassing and outgassing processes, in units of petagrams, or gigatons, of carbon per year (Pg C/y). "Org carbon" is organic carbon, and "MOR" is mid-ocean ridges. (b) The annual rate of carbon exchange with the atmosphere from large-scale perturbations compared with the sum of all geologic outgassing processes, in units of petagrams, or gigatons, of carbon per year (Pg C/y). "LIP" is large igneous province. Credit: Deep Carbon Observatory

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600 Years of Grape Harvests Document 20th-Century Climate Change

Climate change isn't captured just by thermometers—grapes can also do the trick.

By mining archival records of grape harvest dates going back to 1354, scientists have reconstructed a 664-year record of temperature traced by fruit ripening. The records, from the Burgundy region of France, represent the longest series of grape harvest dates assembled up until now and reveal strong evidence of climate change in the past few decades.

The dates of Burgundian grape harvests record a changing climate. Credit: iStock.com/U. J. Alexander

Science with Grapes

As far back as the 19th century, scientists have been using records of grape harvest dates to track climatic changes.

"Wine harvest is a really great proxy for summer warmth," said Benjamin Cook, a climate scientist at the NASA Goddard Institute for Space Studies in New York not involved in the research. "The warmer the summer is, the faster the grapes develop, so the earlier the harvest happens."

But there are potential pitfalls to using this method, said Thomas Labbé, a historian specializing in the Middle Ages at the Leibniz Institute for the History and Culture of Eastern Europe in Germany and the Maison des Sciences de l'Homme de Dijon in France. For instance, he said, some studies have compiled grape harvest dates from vineyards in different locations. That's problematic because of climatic differences due to latitude—for Northern Hemisphere vineyards, grapes growing farther south tend to ripen earlier than grapes located farther north. Other investigations have relied on secondary sources of grape harvest dates riddled with transcription errors, said Labbé.

Vineyards of an Ancient City

Now Labbé and his colleagues have assembled a 664-year record of grape harvest dates for one French city using information gleaned from original sources.

The city of Beaune is an excellent site for long-term analysis of grape harvests, said Labbé. Rows of pinot noir, sauvignon, and Gamay grapes have dotted its slopes for centuries and still do so today. (Dijon, 45 kilometers northeast and the capital of the Burgundy region, isn't as good a site. It has undergone pronounced urbanization since the 19th century and has accordingly lost many of its vineyards.)

"The vineyards still surround the city, so we could extend the series to the present day," said Labbé.

The researchers mined original sources (such as medieval accounts of wage payments to vineyard laborers, city council records, and newspaper reports) to determine when Beaune's grapes were harvested each year from 1354 to 2018. When data were missing from archival records, the researchers used harvest dates from Dijon and adjusted them to account for the capital's more northerly location.

They were careful to analyze each date in the context of history. For instance, the harvests of 1636 and 1637 were "certainly disorganized" by warfare and an outbreak of plague, the scientists concluded. All in all, Labbé and his colleagues recovered harvest dates ranging from 16 August to 28 October.

Outliers "Become the Norm"

Labbé and his colleagues showed that the dates of Beaune's grape harvests correlated strongly with both instrumental temperature records from Paris and tree ring–based temperature reconstructions from western Switzerland. These correlations demonstrate that grape harvest dates indeed are an accurate proxy for local temperature, Labbé and his team concluded. "It's possible to reconstruct temperature backward," he said.

The scientists found that the series of grape harvest dates could be clearly divided into two regimes. Grapes were, on average, picked on 28 September or later before 1988. But from 1988 onward, grapes were harvested roughly 13 days earlier.

"Hot and dry years in the past were outliers, while they have become the norm since the transition to rapid warming in 1988," Labbé and his team wrote in their paper, which was published in *Climate of the Past* (bit.ly/grapes-climate).

It's not surprising that the climate is warming, said Labbé. "The surprise is rather that the grape harvest date series reflects so well the temperature trend of the last 30 years. Global warming is very, very visible."

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

Indigenous Records Reveal New Industrial Pollution Risks

Giant Mine, closed in 2004, dominates the forested landscape just outside Yellowknife, N.W.T., Canada. Credit: Agent Magenta, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Giant Mine was once among the world's most productive gold mines. Until it closed in 2004, the mine produced 220,000 kilograms of gold and more than a thousand times that amount of arsenic.

Highly toxic arsenic trioxide dust was a byproduct of the roasting process used to extract gold from ore at Giant Mine, a facility on the shores of the Great Slave Lake in Canada's Northwest Territories. During its earliest days in the 1940s and 1950s, Giant Mine's smokestack was pumping out as much as 7,400 kilograms of arsenic each day, without any environmental protection or regulation.

Arsenic was carried on the wind and settled across local forests, lakes, and rivers.

Almost immediately, it began affecting people in the surrounding region. Fish from certain lakes were linked to arsenic poisoning. Local precipitation was so contaminated that in 1951, a child died after eating snow riddled with arsenic.

Today debate continues over acceptable levels of arsenic detected in areas surrounding Giant Mine.

Reductive Dissolution

Some arsenic released by Giant Mine was sequestered in sediments on lake bottoms, and some researchers say climate change could cause it to be released.

Longer, warmer summers result in more plant and algal growth, which reduces the amount of oxygen in the lake. Lower oxygen levels create the conditions for a chemical reaction in which sequestered arsenic is released.

"When plant or algal growth reduces the amount of available oxygen, the arsenic can be released through a process called reductive dissolution. It's liberated to a dissolved form and can enter the water," said Jennifer Galloway, a research scientist with the Geological Survey of Canada and an adjunct assistant professor at the University of Calgary.

To better understand the historic climate and how changes in climate are affecting the sequestration of metalloids in the region's lakes, Galloway and Tim Patterson, a professor of geology at Carleton University, needed a historical baseline more robust than what they could obtain using paleoecological tools such as dendrochronology and fossil records. Such tools aren't able to discern key information like the date when lakes froze or whether autumn precipitation fell as rain or as snow.

Collaboration with Métis and Dene

In research recently published in the Polar Knowledge Canada journal *Aqhaliat,* Galloway and Patterson looked to two indigenous communities for help with their 3-year project. Each group contributed a distinct type of traditional knowledge to the collaboration. The Yellowknives Dene First Nation drew on oral traditions of ecological knowledge, whereas the North Slave Métis brought written archival records with detailed weather data.

The Métis are of mixed First Nations and European ancestry, which positioned them to serve as a sort of cultural interpreter between the two groups during Canada's fur trade era.

"Hudson's Bay Company trading posts were often staffed by Métis people," said Shin Shiga of the North Slave Métis Alliance, an organization that represents Métis people in the Great Slave Lake region. "Métis were able to communicate with both European fur traders and indigenous people. At trading posts, they kept detailed records of weather conditions that have been preserved in the archives."

The North Slave Métis Alliance's archives are a repository of daily weather information like temperature, precipitation, and wind speed, as well as the dates when lakes froze and thawed.

Métis also contributed their knowledge of more recent climate conditions to the project.

"A lot of Métis people work on the land today," said Shiga. "Whether they are building roads or working in construction, they're always watching what's happening on the land."

The Yellowknives Dene First Nation community sits on the shores of Great Slave Lake, but the traditional lands of the Dene stretch from the Yukon to Hudson Bay. The community's traditional knowledge holders shared their knowledge of local conditions through interviews.

The Yellowknives observed that not only had the timing of the freeze-up changed but the way that lakes were freezing was changing too. Historically, the freeze-up had occurred quickly: A thin veneer of ice would form in October, and within a few weeks the ice would grow thick enough to drive a truck on. In recent years, the lakes have been experiencing numerous freeze-thaw cycles. Autumn precipitation that once fell as snow is now falling as rain and is melting ice when it does.

This rain keeps water open longer in the fall and means there's less ice to melt in spring, so the water can warm more quickly, increasing the growing season and allowing sequestered arsenic to be released.

"Traditional knowledge told us that freeze-up had changed from mid-October to early November and that it didn't happen quickly as it used to," said Galloway. "That's really important for the mobility of elements. Late fall precipitation falling as rain instead of snow can profoundly impact chemical cycling in lakes."

Jennifer Galloway and Tim Patterson acknowledge the contributions made to their research by Yellowknives Dene First Nation, North Slave Métis Alliance, Polar Knowledge Canada, and the government of the Northwest Territories.

By **Ty Burke,** Science Writer

"Living Bridge" Monitors the Environment and Harnesses Tidal Energy

The Memorial Bridge spanning the Piscataqua River from Portsmouth, N.H., to Kittery, Maine, is equipped with a suite of technologies that makes it unlike any other bridge in the world. It has a tidal turbine and associated deployment platform, two weather stations, and structural, environmental, and marine data sensor suites, said Erin Bell, a professor of civil engineering at the University of New Hampshire and principal investigator on the Living Bridge project.

It's the focus of the project, which aims to show a glimpse of what tomorrow's smart transportation systems might look like (livingbridge.unh.edu).

"Our transportation infrastructure is a huge cost, and it can do more than get us from A to B," Bell said.

Rather than just serving as a means of traversing the Piscataqua River, this "living" laboratory uses acoustic Doppler current profilers to study the river's currents. A conductivity, temperature, and depth sensor is in use, and in addition to providing those types of data, the sensor also measures the water's turbidity and the amount of dissolved oxygen and chlorophyll present in it. The bridge's weather stations provide wind speed, humidity, and temperature data. The structural sensors enable Bell and her colleagues to obtain six to eight "really nice...stress tests" of the vertical-lift bridge every day, she said.

Tidal energy "is the next-generation global engineering technology following wind and solar," said Vincent Neary, who leads Sandia National Laboratories' marine and hydrokinetic technologies research and development projects and isn't involved with the project.

"What is exciting about this is that tidal energy can be very predictable," said Martin Wosnik, associate professor of mechanical engineering at the University of New Hampshire in Durham who was the lead on the Living Bridge turbine install. "Unlike solar panels, which can be unreliable due to cloudy days or bad weather, tidal energy is more stable because we can predict the tides well into the future."

The bridge's inclusion of the tidal turbine is both unusual and remarkable because "it's not an easy thing to do, to put a tidal turbine on a bridge," Bell said. Bridge construction budgets are typically tight, so incorporating this type of renewable energy often seems outside of the scope of these projects, she noted.

Civil Engineering of the Future

Neary and Bell agree that the key to moving forward with projects such as this lies in demonstrating that the benefits of integrating the tidal energy and other technologies outweigh the associated costs. The Living Bridge project aligns well with "a big push" in civil engineering for "multiuse, multibenefit projects," Neary noted.

This project also has tremendous educational value. Middle and high school teachers have used data from the bridge in classroom-based citizen science projects, Bell said. She has also spoken to retirement communities about the project, shown scale models of the turbine to 120 seventh grade students who have visited the laboratory, discussed the project at public meetings, and explained the instrumentation on science cruises of the Portsmouth Harbor.

The bridge is "exciting and innovative enough that folks can learn something from it, whether they're in kindergarten or in their eighties," Bell noted.

Neary said that he loves the educational component of the project because "a lot of our population isn't connected with science and understanding the importance of fact-based and data-based decision-making," and having the opportunity to engage with this or similar projects might change that.

Bell is often asked whether the presence of the sensors and other instrumentation signifies that something is wrong with the bridge, but it's actually quite the opposite: The team saw the opportunity to make the bridge a "living" construction when the bridge structure that preceded it had to be closed and replaced (except for the piers) because of structural deficiencies, she said.

Both Bell and Neary could see a place for similar smart bridges in other communities. Bell said that aside from securing funding, it's critical that others who want to embark on similar projects are able to demonstrate to the bridge owners how the project will add value for them, not just for the researchers.

Neary thinks there are potentially hundreds of places in the United States alone where it might make sense to do similar projects. In an ideal world, he said, "every single bridge should be evaluated" by asking, "Can we have a project here?"

However, "you need money to do it right," he said, and political barriers often get in the way of funding infrastructure.

This "living bridge" is outfitted with structural, environmental, and marine data sensors. It has a tidal turbine deployment platform and two weather stations. Credit: Scott Ripley/UNH

By **Rachel Crowell** (@writesRCrowell), Science Writer

Our Greatest Challenges Require Science, Not Silence

U.S. Congressman Paul Tonko speaking at the inaugural 2017 March for Science in Albany, N.Y. Credit: Rep. Paul Tonko

Scientists have long worked to protect our public health and advance our economy and national security. While doing this vital work, they have also largely avoided the noise and clamor of political debate. As an engineer, I can relate to this preference. However, as a longtime public servant, I have seen how important it is for scientists to speak out. The challenges we face as a nation and world are substantial, and history shows us that they will not be solved without your science and your voices.

In the United States, publicly funded science outside government agencies didn't exist when AGU was founded, in 1919. In fact, its start wouldn't come until early 1941, when President Franklin Roosevelt created the Office of Scientific Research and Development to develop technologies that could help win the Second World War. The first director of that office, engineer Vannevar Bush, allowed the scientists under his direction to pursue the research they deemed most promising. This openness to creativity contributed to an Allied victory while producing major technological advances, including radar countermeasures and the chemical synthesis of penicillin.

A Model for Public-Serving Science

Roosevelt saw the potential for more and asked Bush to craft a model for permanent, federally funded scientific research. The resulting report, "Science—The Endless Frontier," became a road map for the United States of America to advance independent, fundamental, and necessary scientific knowledge for the benefit of all.

In his report, Bush argued that federally funded science should advance three measures: public health, national security, and public welfare. He argued that science could best advance these measures with strong and steady funding and, just as important, freedom from political interference.

Bush's legacy can be seen today in many of the ways we support scientific research, including the independent peer review process we use to allocate grant funding. That approach has contributed to our nation's global dominance in the fields of science and technology.

Unfortunately, these prerequisites identified by Bush—funding and independence—are threatened. Federal research has been a target of political attacks for decades, and the precipitous decline in congressional funding highlights the success of these attacks. In 1965, federal research and development funding represented 1.8% of the U.S. gross domestic product; today it hovers around 0.5%. The Earth sciences represent a small and shrinking sliver of that already neglected total, despite their present and vital importance. As the climate crisis unfolds, the costs of underfunding Earth and space research agencies become increasingly grave.

Science has long weathered such attacks without letting go of Bush's founding principle of scientific independence. Sadly, the disruptions of scientific independence under President Donald Trump's administration have added measurably to these concerns. Under Trump's presidency, political leaders have buried climate data and reports, prohibited use of the terms "science-based" and "evidence-based" in budget documents, and discredited National Weather Service forecasters for presenting factual emergency response information that contradicted outdated forecasts. The president's budget requests have repeatedly proposed to cut both the National Oceanic and Atmospheric Administration's and the U.S. Geological Survey's funding by more than 20%. Our national commitment to public science has fallen far since the days of Roosevelt.

I am fighting to ensure that sound, evidence-based policy is readily available for policy makers and that science advisers are always free to speak the truth.

A National Awakening

These attacks on scientific funding and independence are bad for our health, security, and economy, but they have brought one good out-come: a national awakening of scientists and advocates for strong, smart science policy.

I have been proud to help carry this effort forward in Congress. As chair of the House Energy and Commerce Subcommittee on Environment and Climate Change, I have made science our guiding principle in everything from chemical policy to climate action.

As a member of the Committee on Science, Space, and Technology, I was proud to reintroduce the Scientific Integrity Act to help ensure that our nation's most important science will be conducted, reviewed, communicated to the public, and incorporated into policy making in ways that are transparent and free from political, ideological, financial, or other undue influence.

Today that bill has over 200 cosponsors and counting. We held a hearing earlier this year at which we heard a consistent message from across the political spectrum: Scientific integrity is not partisan. I am optimistic that this message has finally begun to resonate through the halls of Congress, and I look forward to making real bipartisan progress.

I am also fighting to ensure that sound, evidence-based policy is readily available for policy makers and that science advisers are always free to speak the truth. The president's Executive Order 13875 required one third of all federal advisory committees to be dissolved. These panels are made up of scientists and academics who advise federal agencies on how to ensure that their regulations are grounded in the best available research. I responded along with my colleagues Reps. Sean Casten (D-Ill.) and Mike Quigley (D-Ill.) by introducing the Preserve Science in Policymaking Act, which would prevent the president from unilaterally dissolving these vital scientific advisory committees.

We Need Science Advocates

Members of this administration have worked to undermine federal science policy, and the consequences will ripple out long after these leaders have left office. Americans are living—and dying—in the path of unprecedented flooding, raging wildfires, and battering storms driven by Earth's changing climate. More than ever, we need to set aside past disagreements and rise together to meet this challenge. We agree that climate change is real. We agree that humans are driving it. Science has given us this much. But we also agree that we need to build solutions that meet the scale and urgency of the crisis we face. And that means we need more than good science; we also need scientific advocates to confront the large-scale challenges that Vannevar Bush knew federally funded science would have to solve.

Let me be clear: If you care about scientific research, funding, and the continued prosperity of humanity, political apathy is no longer an option.

Earlier this year, I spoke at the Climate Leadership Conference in Baltimore, Md., where I introduced my Framework for Climate Action in the U.S. Congress; this framework outlines how Congress can build legislation drawing on the best science and our common values to combat the global climate crisis. Our Energy and Commerce Subcommittee announced a science-driven target for U.S. climate action of 100% net-zero emissions by 2050, which we call "100 by 50." Achieving this ambitious target will require an equally ambitious plan for widespread transition across all sectors of our economy.

In July the House Science Committee advanced two bills I introduced to move us closer to our "100 by 50" target: the Wind Energy Research and Development Act, which creates an Office of Wind Energy within the Department of Energy, and an amendment to the Fossil Energy Research and Development Act to improve the efficiency of gas turbines. Across Congress, numerous bills are being introduced to reduce emissions, whether through carbon pricing, stringent fuel economy standards, incentives for wind and solar energy, or a host of other measures. These efforts require, and I think reasonably demand, the attention and vocal engagement of the U.S. scientific community.

The challenges we face are vast, our opposition is entrenched and powerful, and it can be easy to doubt our ability to respond adequately. Remember that we have faced challenges at this scale before. We found a cure for polio. We sent humans to the Moon and brought them back safely.

We need more than good science; we also need scientific advocates to confront the large-scale challenges.

Speak Up and We'll Turn Up

We are quantitatively observing a turning point in public opinion in which science, and climate specifically, is driving voters to the polls. A recent Gallup poll found that for the first time, a majority of voters view climate change as either an "extremely important" or "very important" voting issue. The grassroots success of the March for Science revealed popular support for science as a democratic value and for the idea that facts and evidence matter and should form the basis of our governance. More science, technology, engineering, and math (STEM)-trained professionals decided to run for public office in 2018 than ever before, both on their own and with the help of new science advocacy groups such as 314 Action. Many of them won!

The scientific method calls on us to be value-free and objective. I can certainly understand that our nation's scientists might hesitate before wading into the murky world of politics and public policy. Let me be clear: If you care about scientific research, funding, and the continued prosperity of humanity, political apathy is no longer an option. You must learn more about the local, regional, and national political movements, legislation, and policies that affect you. Help shape these factors. Federal science is the product of political choices.

Our U.S. scientific community is at a crossroads. The knowledge it creates is critical for our continued survival, even as its value and independence are being questioned or undermined at a scale unprecedented in modern history. Science is under attack, but it is also our best hope. We have the skill and the organization necessary to get the job done. More than anything, we need our knowledgeable and skilled scientists to be vocal and supportive of putting science first. Add yourselves to the legion of us who are now marching, writing, legislating, and advocating so that federally funded science can direct our efforts to tackle the monumental challenges of this and future centuries.

By U.S. Representative **Paul D. Tonko** (D-N.Y.; Rep.Paul.Tonko@mail.house.gov)

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A GEODATA FABRIC

FOR THE 21ST CENTURY

WE HAVE THE POTENTIAL TO TRANSFORM OUR UNDERSTANDING OF EARTH—IF WE CAN JUST FIGURE OUT HOW TO HARNESS EVER GROWING DATA STREAMS.

By Jeff de La Beaujardière

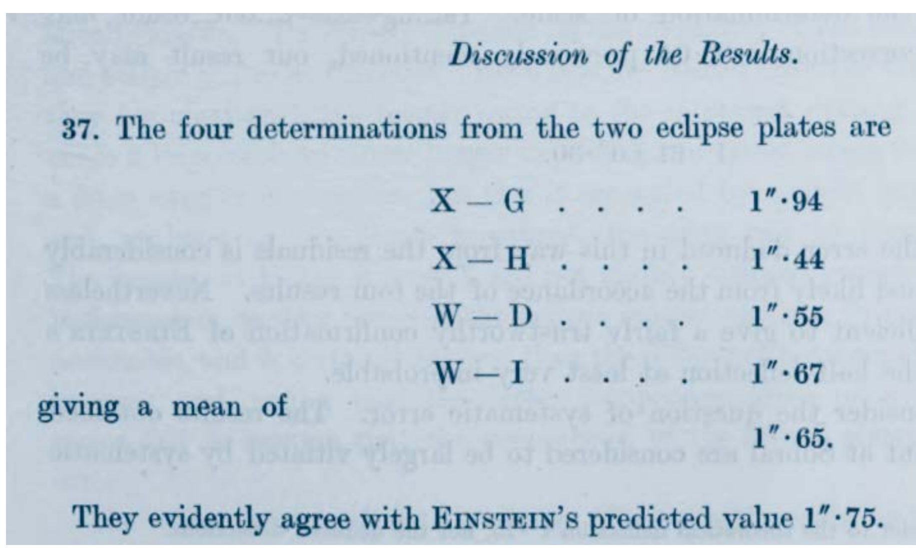
THE NATURE of scientific data has changed considerably since AGU was founded a century ago. Observations then were manual and laborious, data were recorded in paper notebooks and on photographic plates, and the most powerful "computer" was perhaps the Powers Accounting Machine, an electromechanical device for tabulating U.S. Census Bureau data recorded on punched cards. In 1919, the Eddington experiment provided the first observational confirmation of Einstein's theory of general relativity by measuring the deflection of light from stars during a total solar eclipse; the entirety of the published data comprises 20 tables, 2 diagrams, and 1 low-resolution black-and-white photograph [*Dyson et al.*, 1920].

As the digital age arrived and the technology for recording observations progressed, the geosciences and other disciplines began to face the "big data" problem, often characterized by four V words:

- Researchers generate enormous data **volumes** from new observing systems and from simulations run on supercomputers. The sheer size of contemporary data sets makes them expensive to store, difficult to access in more than small subsets, and nearly impossible to ship to all the institutions that would like copies.
- The bewildering **variety** of data sets from sources that use different file formats and organizational systems is a barrier to performing interdisciplinary research and analyzing phenomena that have multiple signals observed by different platforms. In addition, there exist to this day myriad small, manually collected observational data sets that are difficult to integrate [*Genova and Horstmann*, 2016].
- Real-time data are being collected, processed, and disseminated at ever increasing **velocities,** particularly in emergency situations such as earthquakes, fires, and other disasters.
- **Variability** caused by surges in data arrival or user requests poses a challenge for facilities, which must have enough capacity to handle the highest loads yet may be idle during down times.

These issues have escalated into major challenges to performing scientific research and providing accessible, usable information to decision-makers. In just 3 years, the NASA–Indian Space Research Organisation Synthetic Aperture Radar (NISAR) Earth-observing satellite is expected to generate some 85 terabytes of data per day. Supercomputers in the "exascale" range, capable of performing at least 10^{18} operations per second, are under contract to be deployed by 2021 at Argonne and Oak Ridge national laboratories; these will be 1,000 times more powerful than the petascale machines of only a decade ago.

Unless geoscience research in the next century is to be hamstrung by the very data it is collecting, we'll have to find the answers to two questions: How can we provide storage and access for big data? And



Discussion of the Results.

37. The four determinations from the two eclipse plates are

X — G	1″·94
X — H	1″·44
W — D	1″·55
W — I	1″·67

giving a mean of

1″·65.

They evidently agree with EINSTEIN's predicted value 1″·75.

One of the 20 tables needed in "A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May 29, 1919," to confirm Einstein's theory of general relativity. Credit: Dyson, et al., 1920, https://doi.org/10.1098/rsta.1920.0009.

more important, how can we enable "science at scale," such that researchers and other users can work with large, multisource data sets without getting lost in a tangle of incompatible systems?

The Geoscience Advantage

Fortunately, we benefit from two crucial facts. First, the geosciences are not alone in facing the big-data problem. In astronomy, the Square Kilometre Array—an enormous radio telescope with installations in South Africa and Australia—is expected to generate 160 terabytes of raw data per second. The genomics community estimates a need for at least 2,000 petabytes of storage by 2025. In the private sector, Facebook had already accumulated at least 300 petabytes of data as of 2014. Our community will therefore be able to leverage work by others in the same predicament.

Second, the very fact that we do geoscience provides a useful organizing framework: Much of our data are, by definition, based on a time and a place. Every Earth observation, every numerical simulation grid point, has an associated temporal range, a position or region on the planet, and possibly an elevation or depth range. Instead of individual files and collections, we could organize these data within a multidimensional "Geodata Fabric." A good analogy is Google Maps, which integrates detailed road, transit, boundary, river, and hiking trail data from multiple sources, along with satellite imagery, elevation data (terrain layer), in situ data (photos and Street View), ancillary information (businesses and facilities), crowdsourced content (reviews of businesses and places), personal annotations (favorite places), real-time information (traffic), and even basic computation (driving directions). Can we do the same for Earth science?

Creation of a Geodata Fabric requires the geosciences to take a huge leap from where we are now, barely past the stage of paper maps and guidebooks, with disjointed web servers each providing only a tiny portion of the vast body of environmental data. We need a more unified approach such that each data provider—whether in the atmosphere, land surface, seismology, hydrology, oceanography, or cryosphere domain—can contribute to a shared and commonly accessible framework. The same concept could be extended to domains with differing coordinate systems such as other planets or interplanetary space. Some work that clearly demonstrates the usefulness of the approach has already been done along these lines—notably, the Open Data Cube project in Australia—but the concept must be extended to the entire planet and include more than just satellite imagery.

Elements of the Solution

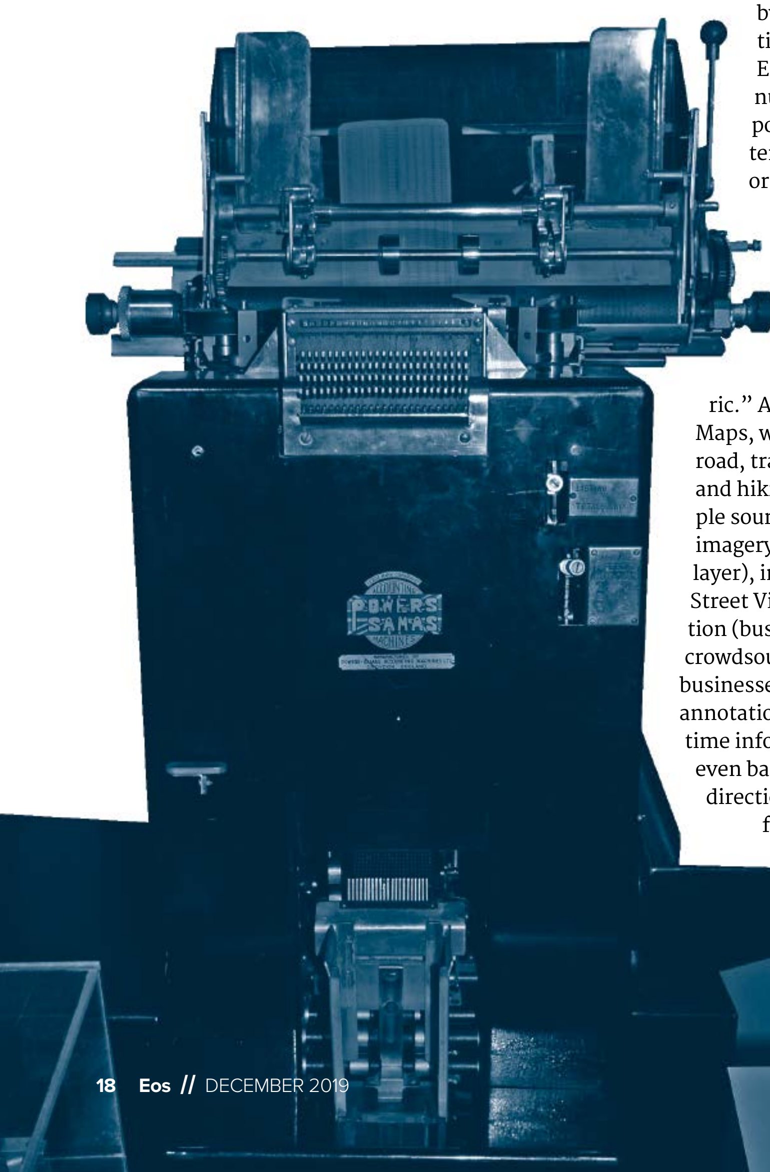
If we want to create this Geodata Fabric, we'll need to rely on automation and standardization at every step as we acquire data; perform initial processing; move them; store them; and enable discovery, access, and analysis. Let's walk through how we might approach four of those steps.

1. A New Type of Storage for Big Data

If you were to log on to any computer storing scientific data today, the organization of the information would typically look a lot like that on your personal computer, with a hierarchy of folders and files. However, these systems become sluggish when they contain billions of files. A better solution, known as object storage, has been adopted by most private companies with huge data needs such as Facebook, YouTube, Netflix, Google, and Amazon.

Object storage uses standard disk drives. Instead of a folder hierarchy, however, it simply has a pool of capacity that can be expanded as needed, has customizable metadata for each object, does not need to actively monitor all the files in the system, and recovers much more easily from the failure of individual drives. Because of this, it is simpler to maintain and better suited for large data volumes.

Each item saved in object storage has a unique ID and a user-defined name, either of which can be used to retrieve the object. For example, an early draft of this article was backed up on Google Drive with the ID "1_8Q2pMN6BHI2N8F5qCaVO5ASdGuGGSOy" and the name "MyDrive/work/AGU/Eos_article.docx." Although it *appears* to be in a folder hierarchy for my personal conve-



The Powers Accounting Machine. Credit: Mahlum/Wikimedia Commons nience, it is merely a blob of data in a huge storage pool.

Lawrence Berkeley National Laboratory in California is among those institutions recommending the use of object storage for big data [*Lockwood et al.*, 2017]. To make the switch, developers will need to slightly modify software that assumes that data are in a traditional file system.

Object storage can be located at the data collector's facility or in the cloud. We use the cloud daily in our personal lives for such data as email, calendars, documents, and photos, but most geoscience institutions still rely primarily on storage hosted on-site. Cloud storage offers three key advantages: The maintenance of the hardware is outsourced to professionals, the amount of available storage is essentially unlimited, and public access can be easily granted.

Whether on-site or in the cloud, object storage will be necessary to accommodate vast volumes of information in the Geodata Fabric.

2. Move the Data Once Or Never

We cannot create a Geodata Fabric if each swath of data is isolated. Instead, we need to perform initial raw data processing at the source and then consolidate the usable information. However, moving huge data sets across the Internet is a slow endeavor. Even with such resources as the high-bandwidth Internet2 connecting some research institutions, overall performance is no better than the slowest link in the path. Traditionally, subsetting services have allowed people to "clip and ship" only what they need, but this doesn't enable large-scale science on multiple large data sets.

Some companies now offer bulk data transfer appliances—literally, disks packed in crates—that can be transported as freight. In 2018, a U.S. Geological Survey facility on the Big Island of Hawaii, threatened by possible lava flow from Kīlauea volcano, used an Amazon Web Services (AWS) Snowball physical transport device to quickly copy critical data to the mainland for safekeeping. In 2017, the commercial satellite company DigitalGlobe was the first to use an even larger AWS capability called Snowmobile. The company copied the contents of 8,700 tapes—nearly 100 petabytes of data—into a 16-meter, fully powered shipping container for transfer to the cloud in a matter of months by truck instead of years via the Internet.

Once the data are consolidated, we can bring the computing to the data such that only the output of the analysis software need be sent to the user.

3. The Cloud Advantage

Traditionally, science facilities provide public-facing web interfaces for preconfigured types of analyses, and perhaps allow authorized users to log in directly and run whatever analysis code they prefer. This type of access does not support customized analysis by unknown external users.

The cloud provides several important advantages. Users can operate directly on the data using whatever software they choose. Processing power can be scaled up or down as needed to accommodate large analyses or spikes in demand. Institutions can focus on science instead of operating hardware and can even take advantage of "managed services" ranging from databases to text, image, and video analyzers and, as of earlier this year, entire satellite ground stations.

A potentially revolutionary concept is known as "serverless computing": Instead of keeping a server running (and paid for) constantly to handle only occasional requests, the cloud vendor runs a shared pool of servers on which you can perform brief computations on data as needed, paying only for the amount of time and memory your function uses. This temporary usage is analogous to renting a Zipcar for an

WHETHER ON SITE OR IN THE CLOUD, OBJECT STORAGE WILL BE NECESSARY TO ACCOMMODATE VAST VOLUMES OF INFORMATION IN THE GEODATA FABRIC.

The Apple II personal computer. Credit: FozzTexx/ Wikimedia Commons hour instead of owning a vehicle that spends most of its time in the garage. For organizations that manage large data collections, there are clear benefits to outsourcing infrastructure and focusing only on data stewardship, access, and analysis.

NASA has been a leader in this area, using commercial cloud servers to store, archive, process, distribute, and manage large volumes of Earth-observing mission data—predicted to be over 45 petabytes per year by 2022 and over 245 petabytes total volume by 2025. The agency's Common Metadata Repository and Earthdata Search services are now running on AWS, with more to come. Kathleen Baynes, NASA system architect, told me, "Beyond consolidating software systems and streamlining processes, we anticipate this effort will provide exciting opportunities to further expand the impact of NASA's Earth Science holdings: introducing new paradigms for interacting with data, improving interoperability, facilitating innovative research, and helping to drive from data toward knowledge."

There are some disadvantages to using cloud computing for analysis. Chief among these is the pay-as-you-go model, with costs not fully known in advance. This is a hurdle in particular for government agencies because of legislation that forbids spending more funds than were allocated by Congress, but it can be reduced or eliminated by prepayment, monitoring, throttling usage if necessary, and efficient system design. Storage costs can be minimized by moving infrequently used data to less expensive tiers of storage or even by discarding unimportant data. Egress costs can be minimized by enabling and encouraging users to compute directly on the data. Computing costs can be minimized through more efficient code, using discounted computing time when the vendor has periods of low demand, and using managed services and serverless functions.

Cloud computing is quickly becoming a viable approach for most science being done today and will be essential for moving data out of institutional silos and into a Geodata Fabric.

4. The Need for Simplicity

Naturally, researchers tend to store the data they collect in ways that make the most sense for their projects. But if we want to establish an easily accessible and broadly usable Geodata Fabric, we must improve standardization and enable a higher level of abstraction. A user should be able simply to ask for—or directly visualize—a desired data set, time range, and area of interest while software behind the scenes automatically provides what was requested.

The National Science Foundation–funded Pangeo project, for example, is "a community promoting open, reproducible, and scalable science." Pangeo allows users to combine a variety of open-source tools such as the Zarr format to break multidimensional data into chunks, the Dask library to read many chunks simultaneously, the Xarray package to address data at an abstract level, and Jupyter Notebook for customizable web-based analysis workflows. The goal is to enable users to explore data interactively without worrying about storage details and to efficiently perform computations over large data sets.

Elizabeth Maroon, a project scientist at the National Center for Atmospheric Research, told me that "for cutting-edge climate science, we need to use large ensembles and explore increasing resolution, and that makes our data sets huge. We are using the Pangeo tools to calculate ocean circulation metrics in our new high-resolution climate model simulations. Without the parallel computation made rel-

The Square Kilometer Array (artist's impression). Credit: Mathieu Isidro (SKA)

atively easy by the Dask package, these metrics would take prohibitively long to calculate."

As data volumes grow, it is becoming increasingly difficult to have knowledgeable people inspect all the data for interesting phenomena. We need machine learning—large-scale, automated analysis of big data—to become commonplace, which can happen only once we standardize and consolidate data storage and access.

Planetary scientists have demonstrated the ability of machine learning to find novel features in multispectral images from NASA's Mars Curiosity rover [*Kerner et al.,* 2019]. Furthermore, some data are of little long-term value, such as long periods of undersea video showing only murky seabed punctuated by the occasional arrival of an interesting creature. Machine learning may prove useful in isolating the most relevant subsets of the data and allowing humans to decide whether to discard the rest.

The Future of Geodata

Our capabilities to collect and store data have evolved greatly in the past century, from penciling observations into paper notebooks in the field to using automated sensors injecting information directly into databases. The cost to store a given amount of digital data has decreased thanks to the increasing density with which we can store it, from the $50,000 5-megabyte IBM RAMAC 350 in 1956 to $50 for a 1-terabyte consumer-level hard drive today. Unfortunately, that rate of storage density is flattening while data volumes continue to grow, but new storage technologies will doubtless emerge over the next century. For example, the University of Southampton in the United Kingdom is working on "memory crystals" that could potentially store hundreds of terabytes of information by etching nanoscale-sized structures in quartz [*Kazansky et al.,* 2016].

Whatever the future holds, it is clear that our geoscience data centers must evolve away from traditional silos of in-house systems offering access only to their own data. We must enable science on high-volume, high-variety, high-velocity, and high-variability data by uniting them from multiple sources, standardizing at a higher level of abstraction, and moving the computation to the data. Embracing a concept like the Geodata Fabric would enable researchers to focus more on the science and less on the plumbing.

We are in dire need of better understanding our constantly changing planet, and that requires that we establish better pathways to information.

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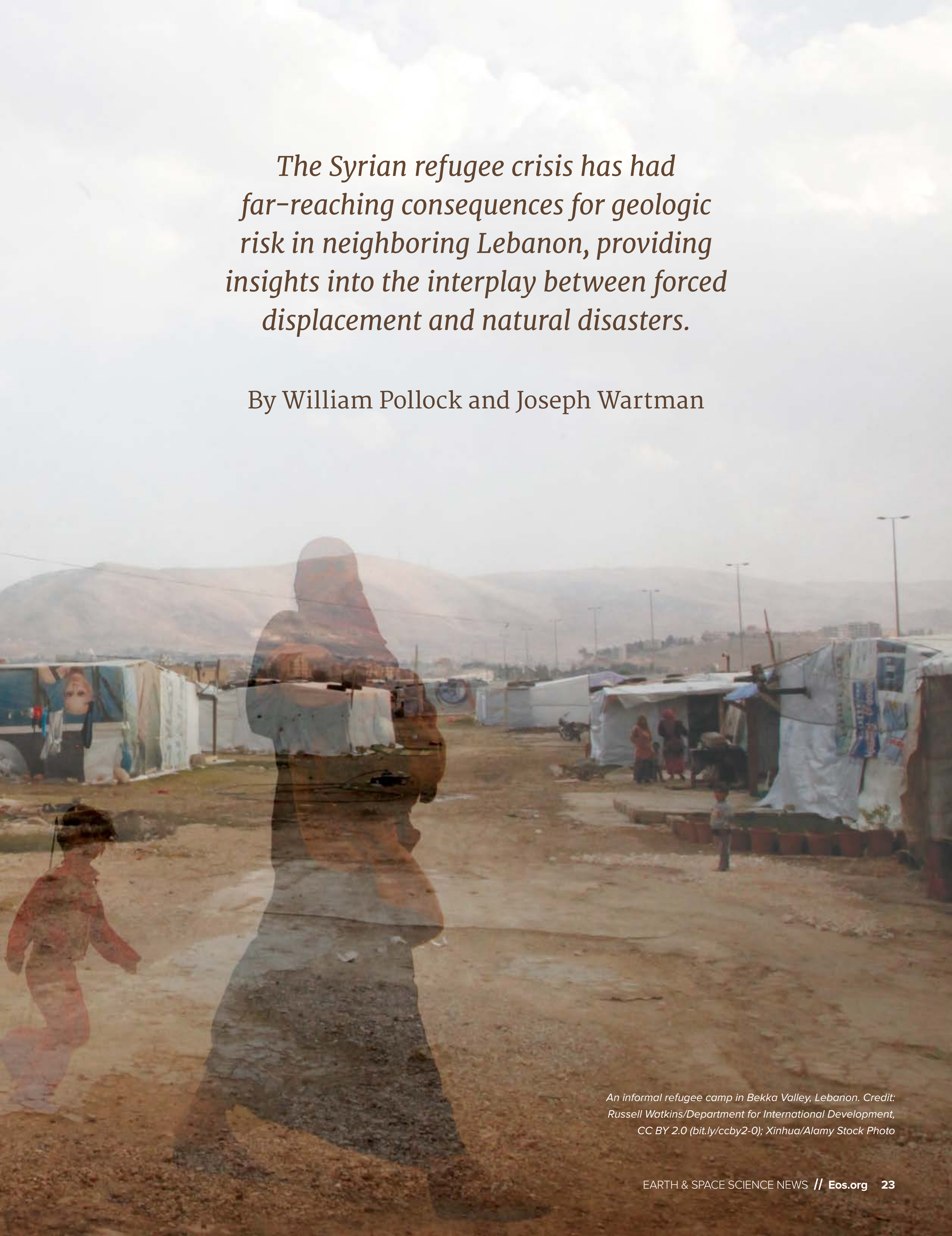
EMBRACING A CONCEPT LIKE THE GEODATA FABRIC WOULD ENABLE RESEARCHERS TO FOCUS MORE ON THE SCIENCE AND LESS ON THE PLUMBING.

monsit/Depositphotos

No Place to *Flee*

The Syrian refugee crisis has had far-reaching consequences for geologic risk in neighboring Lebanon, providing insights into the interplay between forced displacement and natural disasters.

By William Pollock and Joseph Wartman



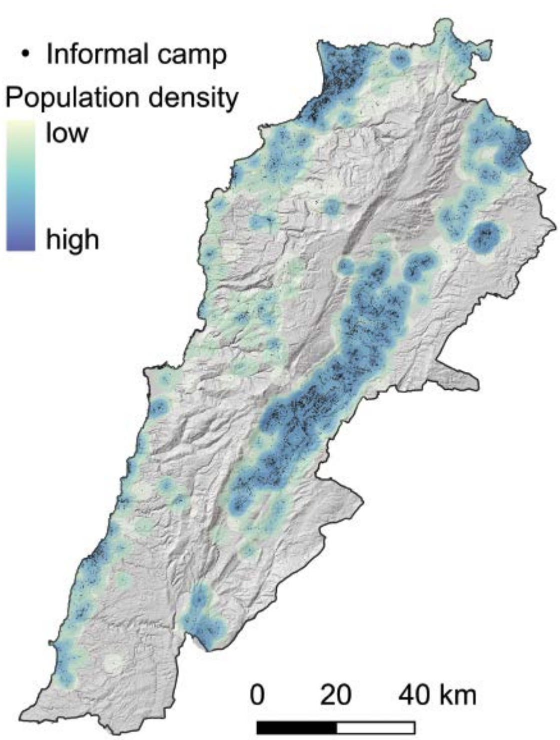
An informal refugee camp in Bekka Valley, Lebanon. Credit: Russell Watkins/Department for International Development, CC BY 2.0 (bit.ly/ccby2-0); Xinhua/Alamy Stock Photo

When winter storm Norma struck Lebanon in January 2019, it unleashed suffering on tens of thousands of Syrian refugees encamped in the barren borderlands between the two countries. Snow collapsed shelters, rivers burst their channels, and landslides spilled from hillsides. At least one child died in the flooding, 1,600 refugees were displaced or evacuated, and thousands of others lived for weeks in ankle-deep water and mud.

For many refugees—not only in Lebanon but worldwide—scenes like these are the tragic status quo. Displaced from their homes by conflict, refugees then endure some of the worst extremes of nature with few of the protections afforded to the rest of the world.

That human conflicts and natural disasters go hand in hand has long been known in the humanitarian sphere. Yet we still cannot adequately explain the intersection of these two phenomena, except in the broadest of terms, much less predict and prevent the catastrophes that result. At the heart of this knowledge gap is the disjuncture between the scholarly fields that study hazards (natural scientists who work to predict the timing, location, and intensity of hazards) and those that study conflicts (social scientists who investigate the sociopolitical settings from which conflicts arise). The two fields have rarely interacted [*King and Mutter,* 2014].

But this separation between the fields is closing. New high-resolution hazard models, coupled with the increase of openly shared humanitarian data, are facilitating greater multidisciplinary collaboration. This is a necessary step in understanding *how* and *why* human conflicts exacerbate natural disasters—and from that understanding will come viable proposals for actions we can take to protect the refugee populations caught in the middle.



Refugee camp locations and population density in Lebanon. Credit: W. Pollock

> *"Displacement exacerbates the frequency and severity of hazards, as high concentrations of refugees can lead to environmental deterioration in areas where natural resources fail to meet demand."*

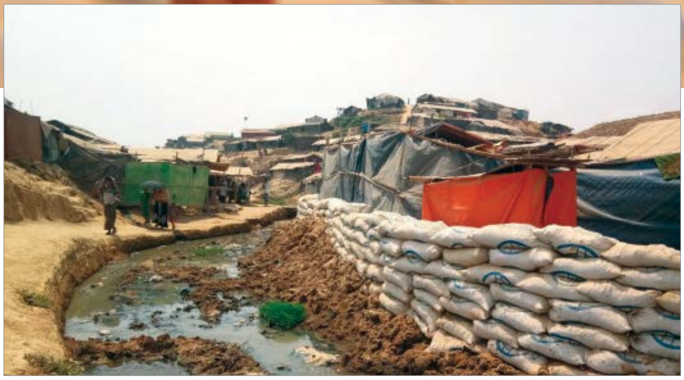
Forced displacement is at a record high and is increasing. The United Nations' (UN) refugee agency reported that at the end of 2018 almost 1% of the world's population, or about 70 million people, was forcibly displaced, compared with around 40 million (0.6% of the world's population) in 2009 [*United Nations High Commissioner for Refugees* (*UNHCR*), 2018a]. Complicating the situation, more intense and more frequent hazards due to climate change are expected to displace increasing numbers of persons each year, mostly in developing countries, where refugee camps are largely located [*United Nations Office for Disaster Risk Reduction,* 2019]. According to UN surveys, refugees already displaced into camps are far more likely than the general population to suffer through natural disasters [*UNHCR,* 2018b].

A Study of Risk: Forced Displacement and Natural Hazards

At the intersection of the social and natural hazard sciences is the concept of *risk.* In its quantitative form, risk describes the likelihood of adverse consequences of an event, calculated by multiplying three factors: the degree of hazard, the exposure of the populace in question, and its vulnerability. Hazard is defined by the *when, where,* and *how large* of a potentially destructive event, such as an earthquake or hurricane. Exposure characterizes the likelihood of a person or community being in the same place at the same time as the hazard, whereas vulnerability describes the conditions that increase the likelihood a person or community will experience impacts from a hazard. For persons already suffering from conflict-driven displacement, that initial state compounds each aspect of risk.

This displacement exacerbates the frequency and severity of hazards, as high concentrations of refugees can lead to environmental deterioration in areas where natural resources fail to meet demand. Tree clearing, unplanned building, and inadequate disposal of wastewater contribute to erosion and flooding. In the 2018 monsoon season, deforested slopes failed in hundreds of landslides in the Rohingya refugee camps of Cox's Bazar, Bangladesh, while compacted soil in high-traffic areas increased rainfall runoff, intensifying flooding in the camps.

Refugees also face heightened exposure to hazards. They are often forced onto marginal lands, such as ravines or hillslopes that others have avoided because of their precarious settings. In addition, unemployment, the high density of people, and the overrepresentation of children among refugees imply that hazardously situated shelters are occupied for most of the day. These elements combine to make it far more likely that many refugees are in the same place at the same time as a natural hazard. In 2006, for example, flooding displaced



The Kutupalong refugee camp in Cox's Bazar, Bangladesh (above). At left, refugees and aid workers build walls from sandbags to mitigate flooding at the Balukhali refugee camp in Bangladesh in 2018. Credits: Russell Watkins/Department for International Development, CC BY 2.0 (bit.ly/ccby2-0); N. Hossain/VOA

100,000 refugees in Kenya's low-lying Dadaab refugee camps and killed three people.

The heightened physical vulnerability of displaced peoples is most visible in the temporary shelters—often makeshift tents—iconic to refugee encampments. These tents, usually made of plastic sheeting, timber, and scrap metal, offer little protection from hazards. In January 2015, winter storm winds collapsed tarpaulin tents in Jordan's Za'atari refugee camp, leaving dozens of Syrian families homeless.

Finally, natural hazards and civil crises can form complex, vicious circles. In 2011, drought in Somalia killed livestock and destroyed crops, leading to more than a quarter million deaths, and armed raids on villages or a desperate search for food forced more than 150,000 from their homes. Somalis fled to Kenya, only to be redisplaced by flash floods that inundated refugee camps.

The Case of Lebanon

With its rugged landforms, Lebanon is afflicted by an array of natural hazards. Two mountain ranges, reaching about 3,000 meters in altitude, span the length of the country. The tectonic system that created the ranges also makes it impossible to live more than 25 kilometers from an active fault. These faults have produced earthquakes that leveled Beirut, Tripoli, and Sidon in historical times—and they will almost certainly rupture again. In addition, these topographic backstops capture moisture-laden clouds from the Mediterranean Sea, producing springtime rainstorms that can drop up to 100 millimeters of rain per hour.

To further explore the relationship between human conflict and natural hazards, we examined the impacts of the Syrian refugee crisis—the largest displacement in recent memory—on neighboring, densely populated Lebanon. Since the start of the Syrian civil war in 2011, Lebanon has absorbed between 950,000 and 1.5 million refugees, swelling its population by 40%. Today one in four people in Lebanon is a refugee.

Lebanon's consociational government—balanced between Maronite Christians, Sunni Muslims, and Shia Muslims—is divided over how to manage the flood of predominantly Sunni Syrian refugees. Lebanon's civil war (1975–1990) is still fresh in its communal memory as a conflict driven in part by the massive influx of Palestinian refugees after the state of Israel was established. Anxious to avoid a reprise of this painful history, the Lebanese government banned formal Syrian refugee camps at the outbreak of the Syrian crisis, leaving the displaced vulnerable to exploitation by landlords and often out of reach of vital aid [*Turner,* 2015].

A destructive debris flow resulting from monsoon floods in Lebanon. Credit: A. Grant

Instead, Syrian refugees settled themselves in urban areas, renting homes and apartments. When the demand for housing overwhelmed supply, refugees turned to garages, barns, and outbuildings. As Syria's civil war raged on and displacement continued, refugees created informal camps, some housing hundreds of families that built fragile shelters out of whatever materials were available.

We examined the risk to refugee populations from earthquake- and precipitation-induced landslides in Lebanon by combining high-resolution topographic data with geologic maps, satellite imagery, and humanitarian data from 2011 to 2018. We used simple, physics-based models to predict landslide initiation under 10 different triggering scenarios: seven rainfall levels corresponding to storms with average return periods of between 2 and 100 years as well as three earthquake shaking intensities that have a 10% probability of occurring within a 50-, 100-, or 500-year period. We also considered different types of landslides, such as shallow and dry slides, debris flows, large slumps, and rockfalls [*Pollock et al.*, 2019]. Further, we looked separately at the precrisis Lebanese population and the current population that includes the Syrian refugees, further subdividing the refugees into those inhabiting preexisting urban infrastructure and those who self-settled in informal camps.

Indiscriminate Hazards, Discriminating Damages

Our findings show that across the country, landslide risk to the population increased by 75% from 2011 to 2018, from a projected 21 deaths per year to 37, a rate that far outpaces population growth.

More revealing, however, was when we normalized risk by population. The probability that in a year, any one person in Lebanon would die because of a landslide increased by about 30%, implying that this fate would befall about 1 in every 140,000 annually. That looks like a small number, but it is about 46 times higher than the per annum individual risk in the United States. Almost all (93%) of the landslide risk in Lebanon comes from frequent small debris flows that are widespread across Lebanon's inland mountain ranges rather than from rare, catastrophic events, such as large earthquakes.

Disaggregating by population to evaluate exposure, we found that although the urban Syrian refugees and the Lebanese population experienced similar levels of risk, encamped Syrian refugees were an order of magnitude more likely to be killed in a landslide than urban dwellers were.

This result is consistent with the findings of other researchers, who observe that sociopolitically marginalized groups worldwide are more likely to die in debris flows. *Dowling and Santi* [2014] suggest that the reason is marginalization of place, forcing those with limited political and economic power to settle in sites more susceptible to natural hazards that are left unoccupied by those with the freedom to live elsewhere. However, we did not find marginalization of place

A simulation modeling debris flows and runout paths (left) in the mountains near El Aabri, Lebanon (right). Credit: W. Pollock to be a significant explanatory factor in the encamped refugees' higher risk.

Simple Solutions

In Lebanon, the key contributor to landslide risk is the vulnerability of shelter. Plastic and timber tents offer little resistance against fast moving debris flows, the most common landslide hazard in Lebanon. We estimate that if all encamped refugees were housed in concrete structures comparable to those in which most urban refugees live, their individual risk would roughly equal that of urban dwellers, despite their rural locations. Although such a sweeping aid effort may be impractical, even a moderate improvement in the shelter quality of encamped refugees could produce dramatic benefits.

This is good news, because the other parts of the risk equation are far more difficult to control. Natural hazards, of course, are difficult to prevent. Exposure is hardly easier to minimize, and it can be exceedingly expensive even to attempt. After a 2005 landslide in La Conchita, Calif., killed 10 people, calls were made to relocate the entire community out of the shadow of the unstable sea bluff. The idea was a nonstarter. Not only would relocation have been prohibitively expensive, but there was also a bigger problem: People did not want to move.

That leaves the conditions of vulnerability as the only factor we can reasonably affect in hopes of significantly mitigating risk. Reducing vulnerability is often the least expensive option and is certainly the most effective when it can be combined with targeted measures to reduce hazard and exposure at the most extreme risk sites. Despite the increased threat of hazards during the 2018 monsoon season in Bangladesh mentioned above, the Rohingya refugees launched a major effort to reduce their exposure and vulnerability and even affect the hazards themselves. In partnership with aid groups and the Bangladeshi government, they upgraded the shelters and roadways in the camps, regraded the steepest hills, installed small-scale drainage systems, planned preemptive evacuations at certain sites, and launched a large landslide education campaign.

Although the season still powerfully affected the camps, it could have been far worse: Of the estimated 200,000 refugees at risk, only one landslide-related fatality was reported in the camps during the 2018 monsoon season.

Complex Implementation

Even the simplest technological solution will be ineffective if it's not brought into the context of the sociopolitical realities of refugee-hosting states.

Recognizing the need for more protective shelter among refugees, the UNHCR partnered with furniture maker IKEA in 2013 to create a durable, mass-producible "Better Shelter." The solution seemed ideal. The hard-sided shelter made of recycled plastic came in two slim boxes, could be assembled in 5 hours by a team of four untrained people using only a hammer, and had 6 times the life span of a traditional UNHCR tent at only twice the cost.

These Better Shelters were more fire and weather resistant than conventional tents, and their hard sides would likely have offered at least a modicum of protection from small debris flows. The UNHCR was set to begin delivery to Lebanon at a time when communities were strapped for resources to care for growing numbers of displaced Syrians.

The Better Shelters barely left UNHCR warehouses before they were banned by the Lebanese government. The shelters were perceived as "too permanent" and feared to risk incentivizing Sunni Syrian refugees to remain in Lebanon, a prospect that powerful Shia and Christian political factions wished to prevent.

> *"We examined the risk to refugee populations from earthquake- and precipitation-induced landslides in Lebanon by combining high-resolution topographic data with geologic maps, satellite imagery, and humanitarian data."*

Words into Action

What can we learn from the case of Syrian refugees in Lebanon? First, an increasing amount of openly available humanitarian data makes it possible to model geologic risk at the scale and pace of refugee crises. We need more collaboration between the social and natural hazard scientific communities to leverage detailed hazard models in understudied and conflict-affected regions.

Second, there is a complex interplay between human conflicts and natural hazards. Although further research is needed to untangle the effects of forced displacement on hazard and exposure, the consistent trend—in Lebanon and elsewhere—is that forced displacement dramatically increases an affected population's vulnerability to natural hazards. Effective and inexpensive solutions to reduce vulnerability are readily available. Thus, vulnerability should be a priority target of interagency refugee aid.

Finally, it is not only scientists who need to collaborate in disaster risk reduction initiatives. Government and community representatives must be equal partners to translate recommendations into durable, socially apropos, and politically viable strategies.

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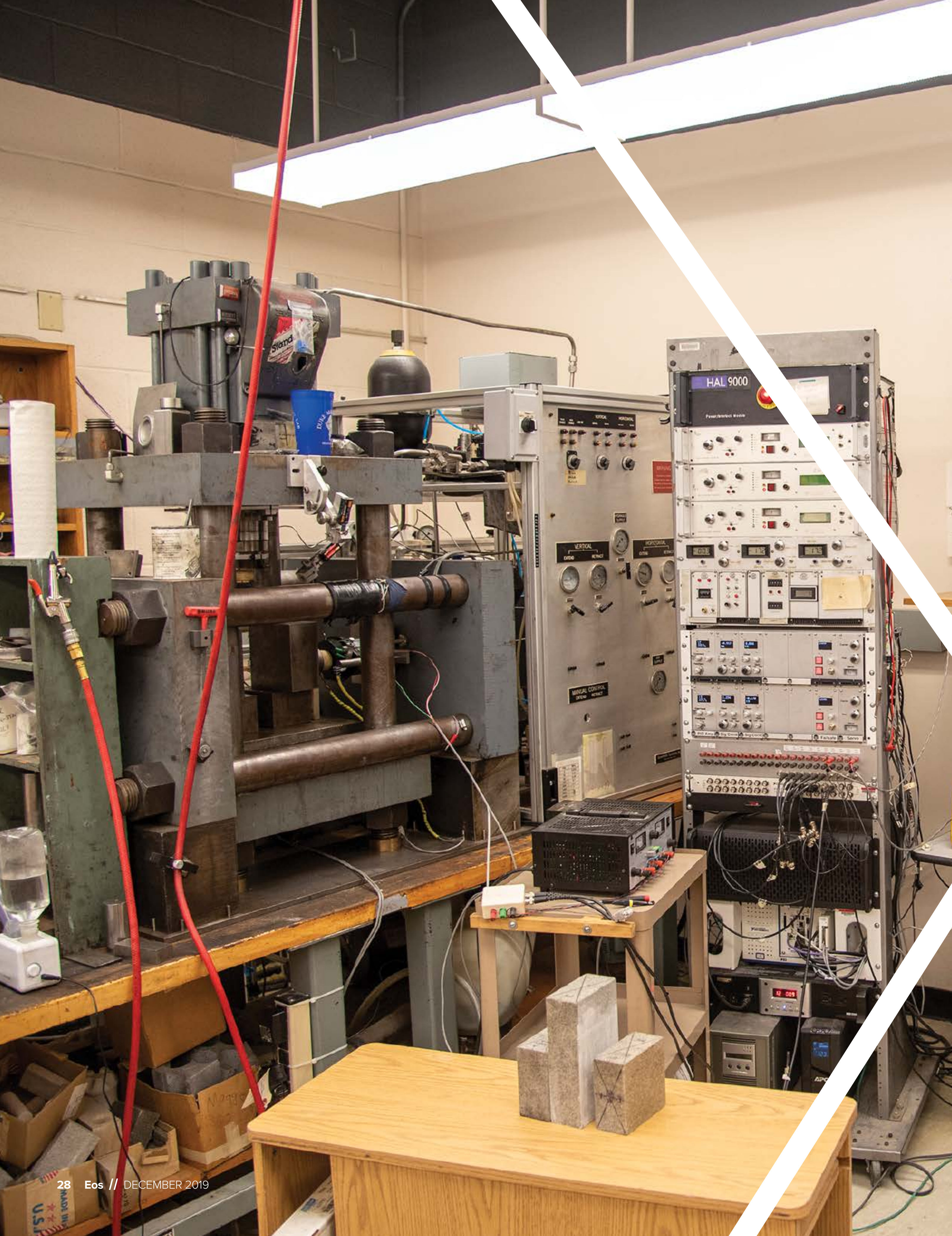
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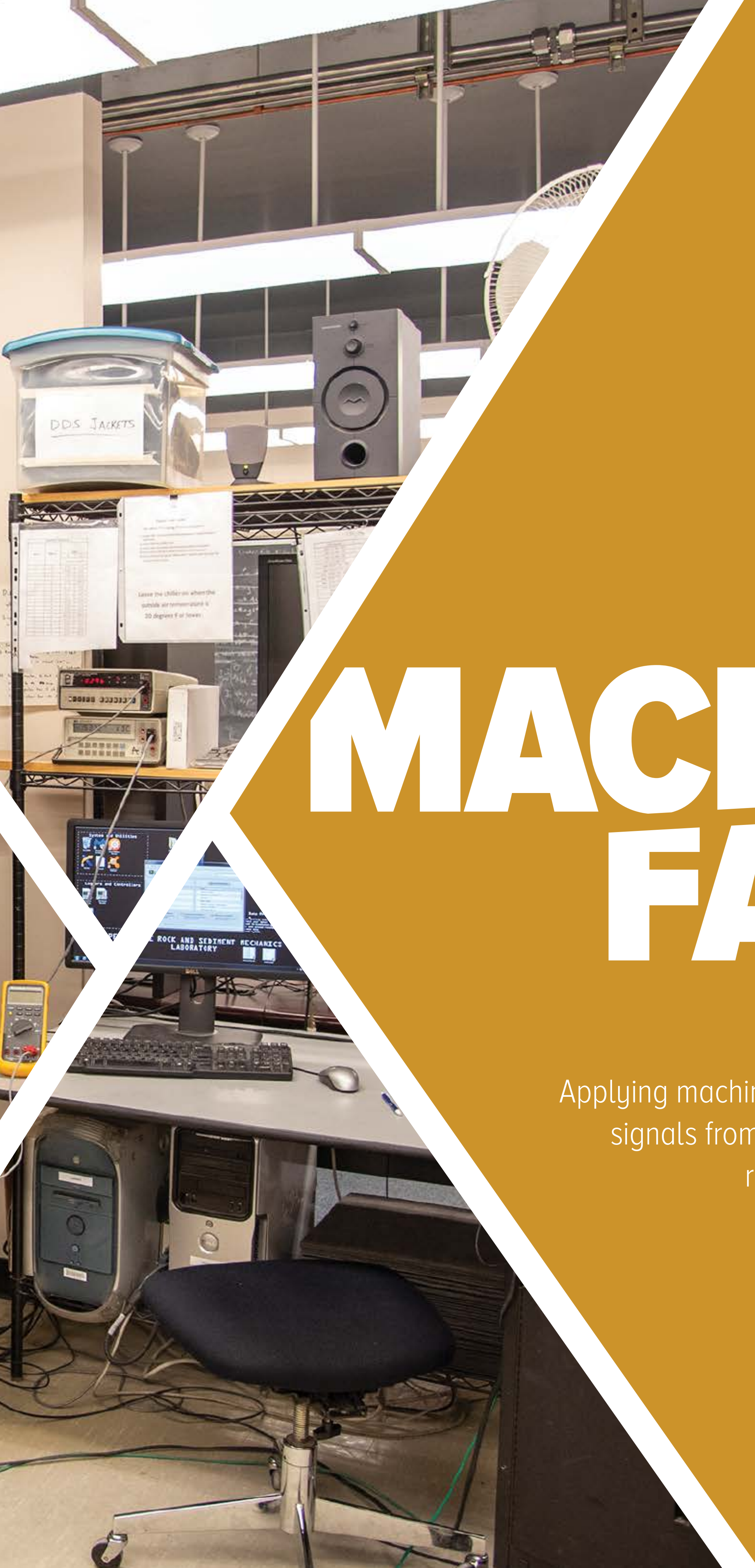


MACHINE FAULT

By Sara E. Pratt

Applying machine learning to subtle acoustic signals from an earthquake machine has revealed big clues about fault behavior in the lab.

The biaxial earthquake machine in Chris Marone's laboratory at Pennsylvania State University, at left, uses steel blocks driven by horizontal and vertical hydraulic pistons to simulate conditions on natural faults. Credit: David Kubarek, Pennsylvania State University

The work the team is doing, "where they can take these laboratory experiments and find information in between slip events, is a breakthrough at the laboratory scale."

A researcher prepares a sample block composed of tiny glass beads for use in the laboratory fault machine at Penn State. Scientists test various materials—both naturally occurring and not—to study their seismic properties and the signals they emit when strained. Credit: David Kubarek, Pennsylvania State University

On a sturdy workbench in seismologist Chris Marone's lab on the fifth floor of the geosciences building at Pennsylvania State University (Penn State) sits a large steel-framed machine with thick hydraulic pistons that force metal blocks and plates to grind past each other under extreme pressure.

The plates, and the ground-up rock between them, are replicas of the slip surfaces and fault gouge found in natural fault systems, but the forces at work when the plates stick and slip are real.

When the device is running, Marone sometimes closes the door to the lab so the loud bangs of "laboratory earthquakes" do not disrupt people across the hall. Lately, however, it has been the quieter sounds emanating from the machine that have caused a disruption in the field of seismology.

In a recent spate of studies, researchers applied machine learning to acoustic emission data from Marone's earthquake machine, as well as from natural faults. The work led to the discovery of a new relationship between a fault's acoustic emissions and its physical characteristics, including its frictional state, its displacement rate, and the timing and magnitude of its next failure.

The work the team is doing, "where they can take these laboratory experiments and find information in between slip events, is a breakthrough at the laboratory scale," said Harold Tobin, director of the Pacific Northwest Seismic Network.

Within the past few years, scientists have used machine learning to identify earthquakes in seismic data at lower magnitudes than were previously detectable (thus producing higher-fidelity earthquake catalogs), estimate fault displacement rates, detect similarities between fast- and slow-slip events, and predict times until fault failure.

These findings from out in the field, along with the novel combination of machine learning and laboratory earthquake setups, have raised tantalizing possibilities for the application of these techniques in developing improved earthquake forecasting and early warning systems, perennial challenges in seismology.

Tabletop Earthquakes

Natural faults are exceedingly complex. The geologic setting, rock type, strain, stress, and friction regimes are different for every fault, making precise predictions of the timing or traits of any given earthquake virtually impossible.

But what if earthquakes could be standardized, reproduced, instrumented, and studied up close in a laboratory? That's just what some researchers—experimental seismologists—have been doing for the past 60 years using a variety of apparatuses and machines to reproduce the high-pressure, high-temperature environments of Earth's interior.

In the middle to late 20th century, experimentalists—including researchers at the University of California, Los Angeles; Harvard University; the Massachusetts Institute of Technology (MIT); Brown University; and the U.S. Geological Survey's Rock Physics Lab in Menlo Park, Calif.—invented machines that revealed new knowledge about rock and mineral physics, including new laws of friction. The descendants of those machines have contributed to the revolution in seismology spurred by the discovery in the past 2 decades that faults can display a spectrum of previously unseen behaviors, including episodic tremor and slip (ETS), low-frequency earthquakes, and slow-slip earthquakes.

Marone's biaxial device is modeled after the first such machine built at Menlo Park. It features two hydraulic pistons, one vertical and one horizontal. The vertical piston forces a steel plate, measuring about 30 × 30 centimeters, down between two steel loading blocks, which are compressed by the horizontal piston. The combined forces place frictional loads on both sides of the center plate, which is coated with various types of ground-up rock, or gouge, found on fault surfaces in nature.

The design allows researchers to apply forces of up to 1 million newtons—comparable to those that occur in some natural systems—while precisely controlling stress and displacement to produce a wide range of earthquake behaviors under repeatable conditions. Among the instruments used to monitor the machine, piezoelectric sensors record acoustic signals that are emitted during experiments.

Marone has worked with the machine for 30 years, first at MIT and then at Penn State, to coax various earthquake behaviors out of it. He now has the ability to reproduce the full spectrum of fault failure modes, from stable creep to the dynamic rupture of regular earthquakes.

"We have to think about all the complexity in real-world fault zones," Marone said, "but many of the things that happen in real fault zones [also] happen in the lab."

From Replica to the Real World

"The bugaboo with any kind of scaling of laboratory slip mechanics to earthquakes is just the incredible jump in scale and the complexity," said Tobin. "The question is, Will it scale to real-world earthquakes?"

One reason seismologists think lab quakes can be a viable model of the physics occurring in natural fault zones and earthquakes is that they exhibit similar frequency-magnitude distributions. Seismic event distributions in both nature and the laboratory are characterized

by
a large number of small quakes and a small number of large quakes. In 1944, Beno Gutenberg and Charles Richter noted that this relationship between frequency and magnitude obeys a power law [*Gutenberg and Richter,* 1944]. And in the 1960s, seismologists, including Christopher Scholz, who would later become Marone's doctoral adviser, discovered that this frequency-magnitude distribution changes before an earthquake.

We've known for 50 years that this relationship "changes subtly and systematically during laboratory earthquakes," Marone said. "But we didn't know how or how much it has to change, so it didn't have any predictive value."

That acoustic signals emanating from faults exhibit a similar pattern has also been known since the 1960s [*Lei and Ma,* 2014], leading seismologists to posit that the signals could provide valuable information about a fault.

Melding Machine and Machine Learning

About 5 years ago, Paul Johnson, a geophysicist at Los Alamos National Laboratory (LANL) in New Mexico, found himself stuck as he was studying how acoustic emissions might be used in earthquake forecasting.

"We were kind of running in circles with the same data sets, and I just didn't know what to do," he said. A colleague suggested that Johnson look into applying machine learning "to let the signal tell you what information it contains."

Johnson began talking to other physicists, materials scientists, computational scientists, and mathematicians about the possibility. Bertrand Rouet-Leduc, then a graduate student at the University of Cambridge in the United Kingdom using machine learning techniques to improve gallium nitride LEDs, took an interest.

A rock sample is sandwiched between sensor-equipped steel plates prior to testing. Credit: David Kubarek, Pennsylvania State University

At about that same time, Marone gave a talk at LANL, after which Rouet-Leduc, who is now a postdoctoral researcher at LANL, approached him.

They discussed how machine learning requires very large data sets to train algorithms, posing a challenge for studying natural fault systems, where ruptures often have recurrence intervals of tens to hundreds of years. Continuous seismic monitoring, which today detects many earthquakes not previously recorded and helps supply such data sets, has been available only for the past few decades or so. Rouet-Leduc told Marone that to accurately train and test an algorithm, data from hundreds of events would be needed. “I said, ‘I can give you 500 earthquakes,’” Marone said.

Within a few weeks of beginning the project, the researchers had developed their first machine learning model using a “random forest” decision tree algorithm. And they were seeing intriguing results, with the model accurately predicting friction on the laboratory fault. “That’s how quickly it happened,” Johnson said, “and suddenly [this research] exploded.”

The Noise Is the Signal

The researchers set to work applying the algorithm to the much larger data sets supplied by Marone’s model fault. They first trained it to look at hundreds of statistical variables—such as amplitude, mean, median, variance, and standard deviation—that characterize the faults’ acoustic signals and to identify patterns or relationships between those variables and selected traits, such as shear stress and ground displacement. After training the algorithm on part of a data set, they tested it on another part that the algorithm had not yet seen.

Previous work [*Dieterich and Kilgore,* 1996] had found that you can derive the friction on the lab fault “from the amount of foreshock activity right before the main event, but not during the rest of the cycle,” Rouet-Leduc said. The new research revealed a previously unknown fundamental relationship between the sound emitted by the laboratory fault and its physical state *at all times,* the team reported in *Geophysical Research Letters* in September 2017 and February 2018 [*Rouet-Leduc et al.,* 2017, 2018].

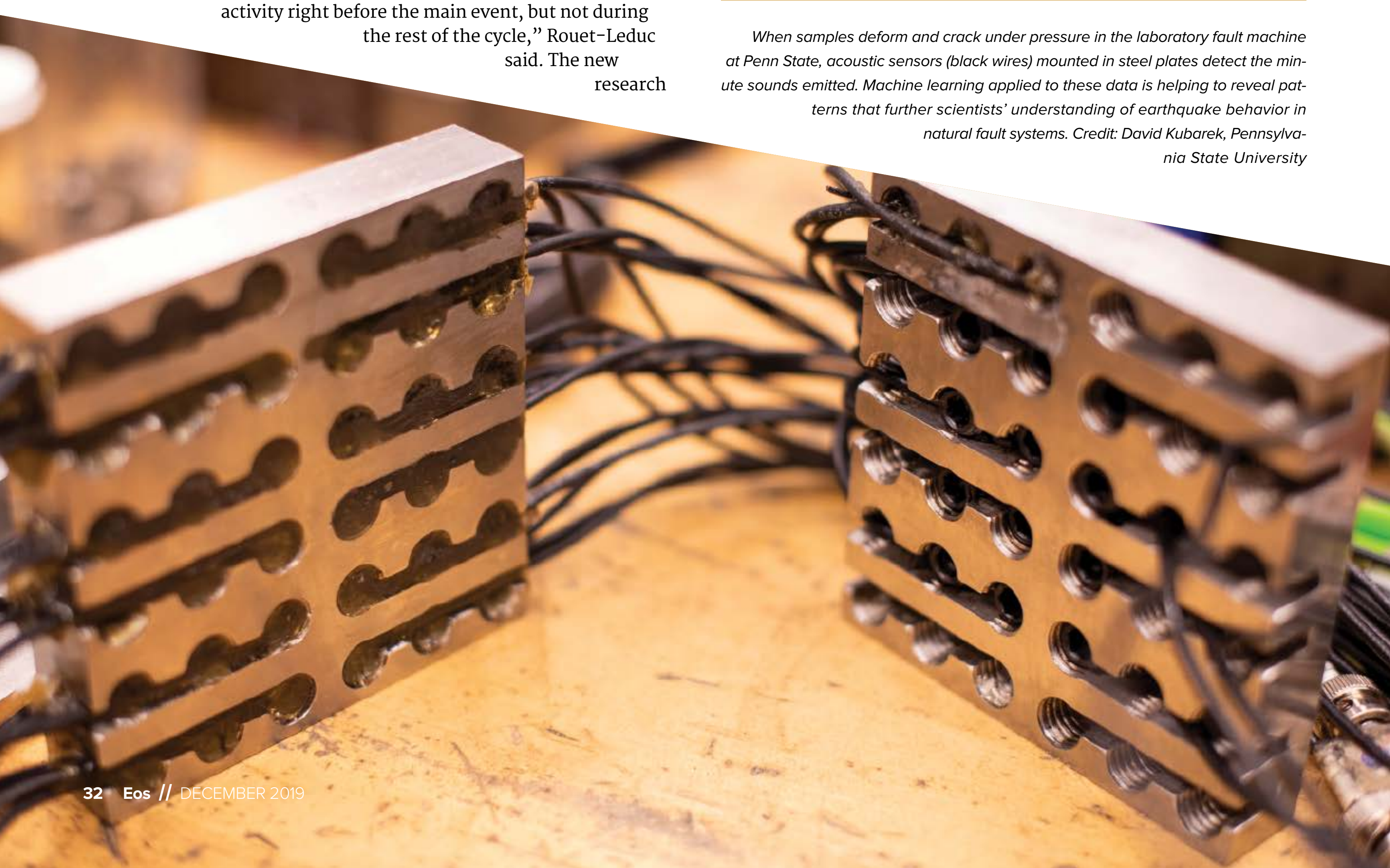
The researchers identified signals previously thought to be “noise” that actually “carry information about the state of the fault,” said Greg Beroza, a seismologist at Stanford University who is not involved in the work. “By discerning relationships between these newly recognized signals and slip state, they were able to forecast, for example, the time of failure in a laboratory setting.”

“We were stunned when we started to see these results,” Johnson said. The team had previously looked at acoustic signals using conventional techniques like Fourier analysis and had found nothing. “I couldn’t believe that the signal that we had discarded was the most important signal in the system.”

Contrary to expectations, the results also overturned a long-standing idea that locked faults repeatedly build up stress until they overcome static friction, rupture, slip a little, and then become locked again.

“That’s not what’s going on in the faults we’re looking at in the laboratory or with slow slip in the Earth,” Johnson said. “What’s happening is the fault is slipping all of the time and radiating this signal that’s telling us about the fault physics” and about an upcoming failure.

The next step was to train and test the algorithm on acoustic signals from a natural fault system. For this, researchers turned to the Cascadia subduction zone (CSZ), the massive subduction zone that poses significant seismic and tsunami hazards for communities all along the Pacific Northwest coast.



When samples deform and crack under pressure in the laboratory fault machine at Penn State, acoustic sensors (black wires) mounted in steel plates detect the minute sounds emitted. Machine learning applied to these data is helping to reveal patterns that further scientists’ understanding of earthquake behavior in natural fault systems. Credit: David Kubarek, Pennsylvania State University

Machine learning requires very large data sets to train algorithms, posing a challenge for studying natural fault systems, where ruptures often have recurrence intervals of tens to hundreds of years.

The fault zone hasn't experienced a megaquake since January 1700, but it does exhibit ETS episodes on cycles of 13–14 months, which have been recognized since 2001 and provide a good stream of data to analyze.

"What we find using machine learning is that we are able to dig out additional signals at all times that inform us on the state of the fault," said Rouet-Leduc. He and his colleagues published their investigation of the CSZ in *Nature Geoscience* in January 2019 [*Rouet-Leduc et al.,* 2019].

The researchers were able to connect the acoustic signal generated by tremor with the slow-slip fault displacement measured by GPS.

"It has been known for a while that there is a proportionality between slow slip, as measured geodetically, and tremor, as measured seismically," Beroza said. "What's new in this study is that the proportionality appears to be continuous. That is, even when there is no clearly identifiable signal, such as a tremor burst, there is a relationship between the weak seismic shaking and the geodetically measured slow slip," he said. "This is suggestive of the relationship seen in the laboratory."

Deep Learning on Deep Quakes

The researchers are now applying machine learning to other longstanding questions about fault behavior.

Claudia Hulbert, a doctoral student at LANL and École Normale Supérieure in France, used the random forest algorithm and additional lab earthquake acoustic data to examine and compare characteristics of fast and slow earthquakes.

Slow earthquakes occur deep in fault zones and exhibit kilometers-per-day velocities rather than the kilometers-per-second speeds of regular quakes. They are of interest to scientists because they alter the stress on shallower, locked portions of faults and often precede major earthquakes.

Hulbert and colleagues reported, also in *Nature Geoscience* in January 2019, that different types of fault slip share similar mechanisms [*Hulbert et al.,* 2019]. This "suggests that catastrophic earthquake failure may be preceded by an organized, potentially forecastable, set of processes," the team wrote.

They also used machine learning to probe connections between episodic tremor and slow earthquakes. In the authors' latest paper, submitted to *Geophysical Research Letters* in August, they used a new method of machine learning, a convolutional neural network also called "deep learning," to detect tremor in the seismic signal from slow earthquakes in Cascadia.

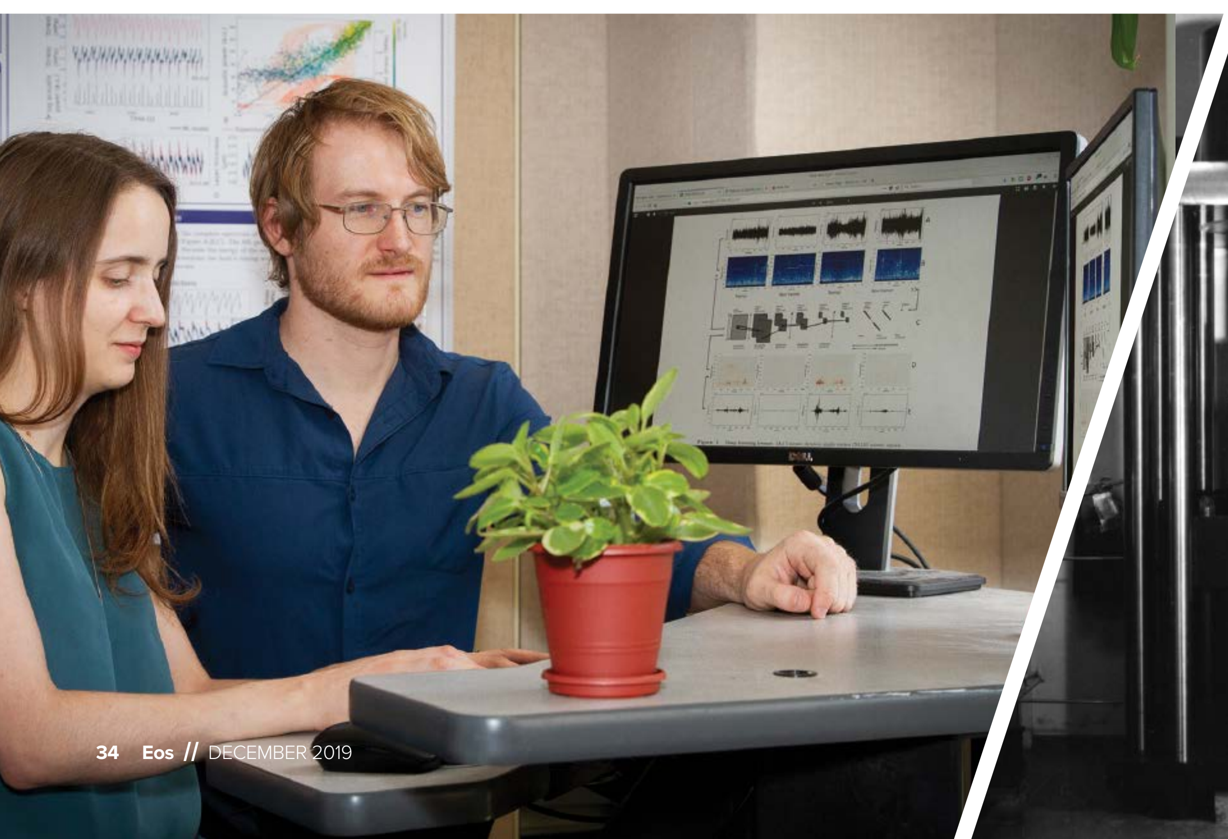
Like the random forest method, the deep learning model is trained. But unlike random forest, in which researchers prescribe which variables the algorithm looks at and the outcomes it should look for, a deep learning network independently determines what patterns and connections are significant.

The advantage of the random forest approach is its transparency, but the disadvantage is that researchers may not think to consider important aspects of the data, Beroza said. "Deep learning has the disadvantage of being opaque in the sense that it is not always clear how a prediction is being made," he said. However, "the algorithm is free to explore relationships between data and predictions that a researcher may not have thought to explore."

Using data from multiple seismic stations in Cascadia containing known slow earthquakes, Hulbert and colleagues trained the neural network to identify tremor. The algorithm was then able to isolate tremor in other Cascadia seismic data from just a single station. Without any additional training, the algorithm was also able to identify tremor in data from the Shikoku subduction zone in Japan and from the San Andreas Fault in California—two very different tectonic settings—suggesting that the characteristics of the acoustic waves produced by tremor are universal.

Using sensitive electronic controls (below), researchers can apply forces of up to 1 million newtons while closely controlling stress and displacement on samples in the fault machine to produce a range of earthquake behaviors. Credit: David Kubarek, Pennsylvania State University


HAL 9000



“The real Earth is a hot mess, with strong geologic variations, varying amounts of pore fluids, and…complex fault systems that interact strongly.”

“It’s very exciting to me that the same kind of observation they made in the laboratory applies to Cascadia,” Tobin said. “Again, the caution I would say is that tremor is not the same as the regular large earthquakes that we worry about.”

The (Seismic) Wave of the Future

Whether the research combining seismic data—from both lab-generated and natural earthquakes—with machine learning will ultimately allow scientists to predict earthquakes, including destructive subduction zone megaquakes, is, of course, a fundamental question for the team, Johnson said. However, he added, the primary goal right now is to improve our basic understanding of fault physics.

Beroza said that the work may contribute to improving the rapidity of earthquake early-warning systems but that he’s not holding his breath that it will suddenly revolutionize earthquake forecasting.

Scientists have been simulating faults in the lab and applying novel analytical techniques to the resulting data for decades. (Clockwise from top) Chris Marone prepares for a test run on the fault machine in his lab at Penn State. Geophysicist James Byerlee stands beside a machine at the U.S. Geological Survey’s campus in Menlo Park, Calif., circa 1970, which he and others used to study the strength deformation and frictional behavior of rocks. Claudia Hulbert and Bertrand Rouet-Leduc, of Los Alamos National Laboratory in New Mexico, apply machine learning to fault data. Credit: (Clockwise from top) David Kubarek, Pennsylvania State University; U.S. Geological Survey; Los Alamos National Laboratory

“The laboratory systems they have studied are controlled experiments in relatively clean systems where the samples are isolated and easily observed,” Beroza said. “The real Earth is a hot mess, with strong geologic variations, varying amounts of pore fluids, and…complex fault systems that interact strongly.” Still, he noted, “the laboratory experiments are highly motivating and highlight important aspects of the system that we should look for in the real Earth.”

Although there are currently no fixed plans to develop a practical application based on the team’s machine learning algorithms, it’s possible it could be used for real-time monitoring, Rouet-Leduc said. “That’s something we have in the back of our mind.”

Meanwhile, the team’s flurry of recent studies, as well as a range of other efforts to integrate machine learning into the geosciences, could portend a tipping point for its use in the discipline.

“We’re seeing really just the beginning. This is going to completely take over all of science, and certainly geoscience, in the next 5–10 years,” Johnson said. “Everybody is going to be using this as a basic tool set to work with their data.”

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Sara E. Pratt, Science Writer

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Communities Thrive With Thriving Earth

By Korena Di Roma Howley

As AGU celebrates 100 years, its Thriving Earth Exchange is setting a foundation for the future, partnering with community leaders to bring scientific solutions to pressing local issues.

Opposite (clockwise from top left): Photos courtesy Coalition for Wetlands and Forests; Gloria Horning; Lemmon Valley Flood Relief/Assistance; A Community Voice; Flood Forum for Connellsville, Pa.; A Community Voice

When Hurricane Harvey hit Port Arthur, Texas, with a record-shattering 1.5 meters of rainfall in August 2017, the home of local activist and community organizer Hilton Kelley was among thousands that flooded in the coastal city. "I had 3 feet of water in my house," Kelley said.

Floodwaters ultimately affected about 80% of the city's homes. "This is something that is still impacting our community two years later," Kelley said. "It's hitting everybody directly."

Kelley, founder and director of Community In-Power and Development Association Inc., has long advocated for environmental justice in Port Arthur's lower income and predominantly African American neighborhoods, where proximity to oil refineries has led to higher than average cancer mortality rates within the state of Texas.

When Harvey brought flooding that displaced neighborhood residents, Kelley was quick to speak on their behalf. His efforts soon caught the attention of Harriet Festing, cofounder of the grassroots advocacy nonprofit Anthropocene Alliance. Festing was interested in assembling a network of flood survivors and was just getting started with the project that would become Higher Ground, which provides community groups with the tools they need to take action against flooding. "My experience with Harriet is, number one, she's very determined," Kelley said. "She was very adamant about doing something in a big way."

Festing worked with Kelley to establish what Port Arthur flood survivors needed most—from clothing to relocation out of flood-prone areas—and offered to direct him to resources.

One of those resources was AGU's Thriving Earth Exchange.

"The partnership has been transformational for the whole organization," said Festing, a former British government civil servant who has spent 25 years managing climate change programs. "It's had a massive influence on our program."

Community First

Five years ago, as AGU geared up to celebrate its Centennial in 2019, organization leaders wanted to find a way to both recognize the achievements of the past century and help set a foundation for the next 100 years. Thriving Earth Exchange grew out of that goal, and this fall the initiative celebrated a fitting milestone: 100 projects undertaken around the United States and the world.

The program brings community leaders and scientists together to solve, at a local level, some of the most important challenges facing

Higher Ground, founded by Harriet Festing (right, with colleague Gloria Horning in Pensacola, Fla.) is the largest flood survivor network in the country, working with 50 advocacy groups in 22 states and helping to catalyze the United Flooded States of America campaign and 15 projects in collaboration with Thriving Earth Exchange.

regional populations in the 21st century, including those related to climate change, natural resources, and pollution. Many of the communities Thriving Earth Exchange works with are historically underrepresented and underserved, and the partnership facilitates action on priorities set by those communities.

Some, like Port Arthur, seek scientific support in the form of maps or studies—tools that can empower communities making a case for policy change. Others need assistance interpreting and communicating complex data or navigating unfamiliar technical terrain and infrastructure challenges. Some want help collecting and interpreting data about the places where they live, work, and play.

Residents of Evanston, Ill., who have long grappled with the damaging effects of a waste transfer station, sought scientific expertise for an environmental monitoring study. The city's partnership with an environmental engineer through Thriving Earth Exchange resulted in a sampling plan and equipment recommendations based on contaminant levels identified during the project.

In Flint, Mich.—which has struggled economically for decades and in 2014 began a protracted battle against lead-contaminated drinking water—Thriving Earth Exchange paired Michigan-based landscape architects with a community organization that wished to design and build the city's first green roof. Community pride and empowerment are at the core of the project, which will provide an energy-efficient solution for a space that serves at-risk youth.

The common thread across all of Thriving Earth Exchange's projects? Science.

"Science is a kind of knowledge, a kind of power," said Raj Pandya, director of Thriving Earth Exchange. "We want to make sure that every community that wants to has the ability to frame and investigate their scientific questions."

Community science, the concept at the heart of Thriving Earth Exchange, "always starts with community priorities," Pandya said. "[It's about] sitting down with communities, understanding what their priorities are, what they want to accomplish…then designing science projects that help them achieve those aspirations. It's a very collaborative, cogenerative process that really respects community agency and community knowledge."

Working in direct partnership with volunteer scientists drawn from Thriving Earth Exchange's extensive network, civic leaders and activists establish shared values and goals and implement a plan that will produce concrete results over 6–18 months. In some cases, a project will kick-start additional conversations, producing the ripple effect of community science.

A Flood of Possibilities

Festing's Higher Ground is one example of how many lives the ripple effect can touch. Today the organization is the largest flood survivor network in the country, working with 50 advocacy groups in 22 states and helping to catalyze the United Flooded States of America campaign and 15 projects in collaboration with Thriving Earth Exchange.

According to Sarah Wilkins, a Thriving Earth Exchange project manager, the initiative's collaboration with Festing is unique. "Harriet is able to connect us to people who are dealing with these things on the ground and who are incredibly fired up and ready to address the issue," she said.

Festing "made every difference," said Susan Liley, cofounder of Citizens' Committee for Flood Relief (CCFR) in De Soto, Mo., where frequent flash flooding of the Joachim Creek has claimed three lives since 2003 and has destroyed and continues to endanger homes and businesses. Festing connected Liley with Thriving Earth Exchange, and today CCFR works with a team of four U.S. Geological Survey (USGS) and Saint Louis University scientists.

Since the committee's inception, action by Liley and cofounder Paula Arbuthnot has set in motion the development of a U.S. Army Corps of

Hilton Kelley, founder and director of Community In-Power and Development Association, Inc., has long advocated for environmental justice in Port Arthur, Texas. When Hurricane Harvey brought flooding that displaced neighborhood residents, Kelley was quick to speak on their behalf.

Flash flooding of the Joachim Creek in De Soto, Mo. (above in 2013) has claimed three lives since 2003 and has destroyed and continues to endanger homes and business.

Engineers floodplain management plan, the installation of a USGS flood alarm system, and zoning analysis by the city and county.

"The niche that needed to be filled was one of education," said Robert Jacobson, a USGS research hydrologist at the Columbia Environmental Research Center who was matched with CCFR through Thriving Earth Exchange. As part of the project, Jacobson and his team interpret and communicate technical and scientific data for CCFR and the wider community.

"Ultimately, our goal is to provide the citizens of De Soto with a better understanding of their risks," he said. They do this in part by attending committee meetings, answering questions, addressing concerns, and giving presentations on topics like climate change.

"They lead us through [the project] every step of the way," Liley said.

For Jacobson, working with Thriving Earth Exchange has provided an opportunity to expand his work beyond research and see from another perspective the issues his team is tackling. "It's useful for us to just put on another set of lenses, to get a sense of where that connection is between science and society," he said. "I think [there are] thousands of other small towns—and other communities—that would benefit from this sort of interaction."

Liley agreed. Through Facebook, she connects with other flood survivor groups, offering them encouragement and gathering ideas for approaches that can be applied in De Soto. "It's not just about the coastal areas," she said. "It's about little towns like ours that flash flood from a little, tiny creek. It's about all of America."

The Total Difference

Although Thriving Earth Exchange began as a national program, it has expanded to include international projects in Africa, Central Asia, Central and South America, and the Caribbean, and the hope is to have an ever-growing footprint around the world.

As global issues like climate change increase the need for resilience and sustainable solutions, cities like Port Arthur and De Soto—and organizations like Higher Ground—will be joined by others driven to take action for the long-term benefit of their communities. And the goal of Thriving Earth Exchange is to be part of their stories.

"We really feel that science can be a useful contributor to local challenges, and the best way to do that is not to tell people what the challenges are but to let the challenges emerge from their own experience and find ways to contribute," Pandya said.

Susan Liley cofounded Citizens' Committee for Flood Relief in De Soto, Mo., where the Joachim Creek frequently produces flash floods. Thriving Earth Exchange connected Liley (center in light blue) with scientists from the U.S. Geological Survey and Saint Louis University.

Festing, who stays involved with the projects she helps facilitate, pointed to CCFR's accomplishments in De Soto as an ideal example of what can be achieved with scientific support. "There's nothing like Thriving Earth Exchange," she said. "It's extremely rigorous, and frankly, that makes the total difference. It wouldn't work if it didn't have that rigor."

How to Get Involved

If you have an idea for a Thriving Earth Exchange project in your community, know a scientist who would like to join the Thriving Earth Exchange network, or would like to apply to be a community science fellow and help guide a project, sign up at thrivingearthexchange.org.

By **Korena Di Roma Howley** (korenahowley@gmail.com), Science Writer

▶Read the full story at bit.ly/Eos-Thriving-Earth

Citizens' Committee for Flood Relief (2). Opposite: Harriet Festing (top); Hilton Kelly (bottom).

CELEBRATING
A CENTURY OF AGU SCIENCE

AGU was born in 1919. Today, we are the largest society for Earth and space scientists, with more than 60,000 members who promote science for the benefit of humanity. For our Centennial in 2019, AGU launched new initiatives and **engaged more than 80 million people around the world** to celebrate the past century of science and inspire us all for the *next* 100 years.

20 AGU SECTION CAMPAIGNS

Members in nearly every section launched their own *Centennial campaigns*, featuring special collections, social media engagement, and new educational tools.

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The **AGU ETHICS AND EQUITY CENTER** launched this year with the cooperation of organizations dedicated to fostering positive workplaces for science.

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AGU opened its new headquarters, the first *net zero energy renovated commercial building in Washington, D.C.*, as a model for its mission of promoting science for the benefit of humanity.

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100 FACTS & FIGURES

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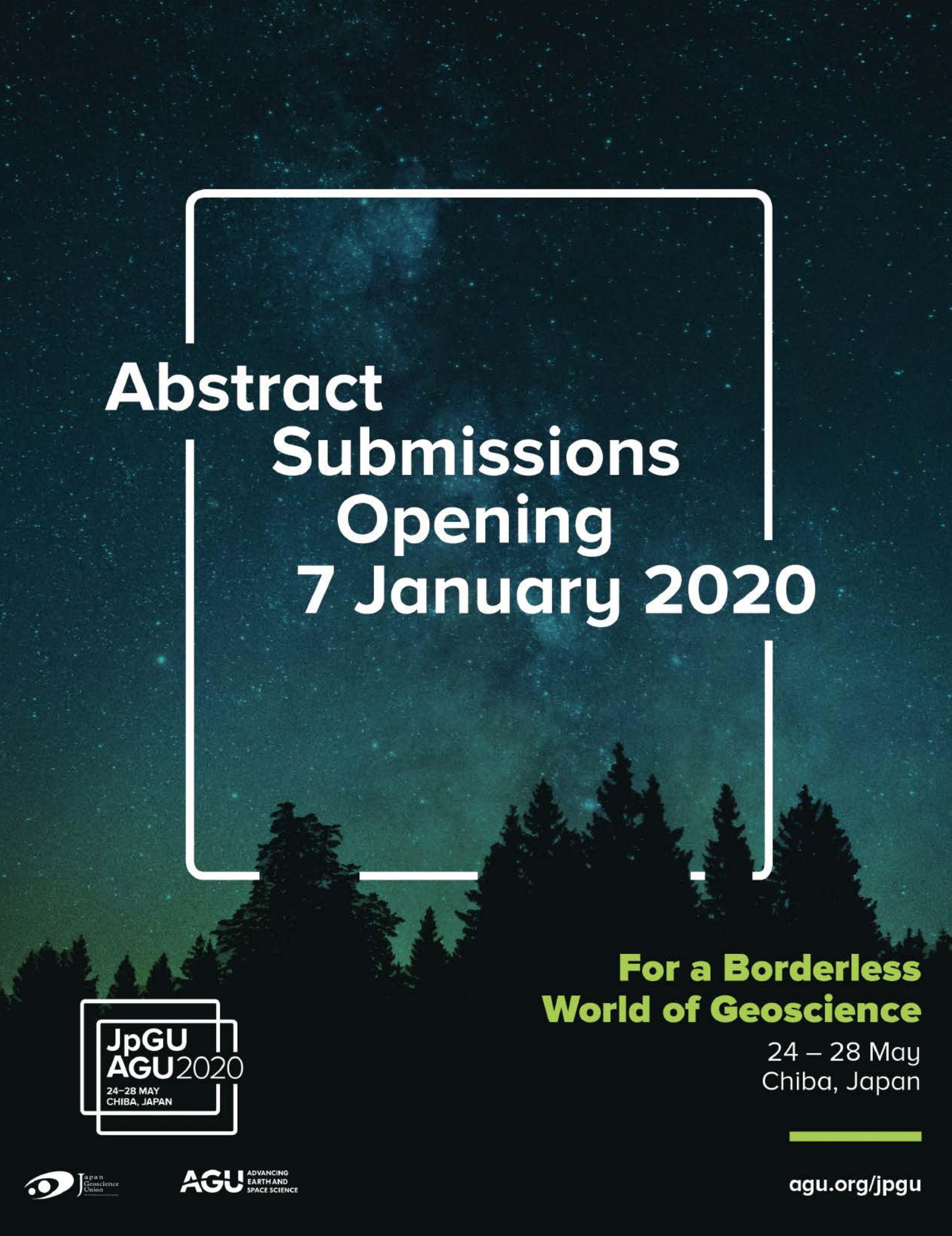
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Charging Thunderclouds Affect Ionospheric Conductivity

Tall thunderclouds are illuminated by lightning near Tarragona on the Mediterranean coast of Spain. Lightning strikes can cause brief perturbations in the ionosphere, but new research suggests that convective updrafts in thunderstorms can heat the ionosphere and cause longer disturbances. Credit: © Oscar van der Velde (lightningwizard.com)

Scientists have long known that lightning from thunderstorms can cause perturbations in the lower ionosphere, partially ionizing the layer and creating disturbances in radio frequency communications. These disturbances usually occur over timescales of less than 15 seconds. However, scientists have also noted ionospheric perturbations occurring over timescales of several minutes, coincident with thunderstorms. Because of the longevity of these signals, it's unlikely that they are caused by single lightning strikes; rather, they appear to result from the electrical activity of a thunderstorm as a whole.

Koh et al. provide the first analysis of this type of long-term, lower atmosphere–ionosphere energy coupling and propose that heating observed in the ionosphere results from charges in thunderclouds redistributing as updraft strength increases.

All thunderstorms are built on the upward convection of warm, moist air. This process helps create the separation of electrical charges in storms that can lead to lightning, but even when the spectacular fast discharges do not occur, convective forces still create strong electrical polarization in storm clouds. The new study shows that this type of convection-based charging can also cause heating in the lower ionosphere as the ions there are energized by the electrical activity in the storm below.

The team studied long-wavelength radio wave transmissions from four locations in the United Kingdom and Germany to a single receiver in Bath, U.K., on 27 August 2016 at around noon local time. These radio signals are sensitive to charges in the atmosphere, including the lower ionosphere, and the researchers used them, along with independent electric field measurements from an antenna array in Portishead, U.K., to monitor a strong convective system over southern central England. They observed disturbances in the lower ionosphere occurring on timescales too long to be associated with lightning strikes. The disturbances grew for approximately 1 minute, and then ionospheric conductivity took at least another 200 seconds to return to normal levels.

The researchers note several other mechanisms by which such ionospheric disturbances might occur, such as gravity waves or solar flares, but conclude that the updraft-related mechanism is the most likely. The results, they say, demonstrate a new type of energy coupling between thunderstorms and the ionosphere and offer a more complete picture of atmospheric geophysics. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2019JA026863, 2019) **—David Shultz,** *Science Writer*

Past Climate Sensitivity Not Always Key to the Future

Earth's equilibrium climate sensitivity—a measure of how much the global average surface temperature will rise in response to a doubling of greenhouse gases in the atmosphere—is a key metric that is widely used in economic and policy assessments of global warming. In a 2013 report, the Intergovernmental Panel on Climate Change estimated that climate sensitivity is likely to be between 1.5°C and 4.5°C.

In numerous studies, scientists have attempted to refine estimates of this metric by characterizing climate sensitivity from the geological record during Earth's recent past. Such research, however, has been limited by the fact that during the past 5 million years, carbon dioxide concentrations have not exceeded 560 parts per million by volume (ppmv), a level that is lower than what is projected in many scenarios representing the end of the 21st century.

To develop more relevant climate sensitivity estimates, researchers have begun investigating intervals of time more than 5 million years ago, when Earth's atmospheric carbon dioxide concentrations exceeded 1,000 ppmv. But because factors other than carbon dioxide, such as the brightness of the Sun and the configuration of the continents, can affect climate over such long timescales, it is unclear how applicable the results of these recent investigations are for forecasting Earth's future.

In a new study, *Farnsworth et al.* try to more fully explore the planet's climate sensitivity over geologic timescales by using an ensemble of 19 climate model simulations to examine Earth between about 150 million and 35 million years ago. In the coupled ocean-atmosphere-vegetation simulations, the researchers varied Earth's paleogeography and the Sun's brightness as appropriate for each geologic interval from the Early Cretaceous to the late Eocene and incorporated atmospheric carbon dioxide concentrations set at double (560 ppmv) and quadruple (1,120 ppmv) the preindustrial level.

The results suggested that climate sensitivity during this time frame ranged from approximately 3.5°C to 5.5°C. The authors attribute the observed variation to a combination of factors, including the gradually increasing brightness of the Sun and changes in the arrangement of the continents, which in turn influenced ocean circulation and, because of differences in ocean surface area, the planet's albedo.

The findings indicate that over long timescales, climate sensitivity is strongly correlated to Earth's continental configuration, the Sun's strength, and the background carbon dioxide concentration. This research suggests that within the context of the past 150 million years, the modern estimate of climate sensitivity is relatively low and that ultimately, Earth's past climate sensitivity may not provide a perfect analogue for potential future conditions. (*Geophysical Research Letters,* https://doi.org/10.1029/2019GL083574, 2019) **—Terri Cook,** *Science Writer*

Methane-Releasing Tundra Soils Freezing Later Each Year

Arctic tundra ecosystems are hot spots for production and storage of methane, a potent greenhouse gas. As air temperatures rise, tundra soils may release more and more methane into the atmosphere. These soils freeze for several months out of the year, but new research by *Arndt et al.* suggests that the Alaskan tundra is freezing later each year, resulting in higher methane emissions in the fall.

Prior research has shown that Arctic tundra soils release a significant amount of methane well into the fall season during a period known as the zero curtain. In this window, the timing of which varies depending on location and from year to year, air temperatures are below 0°C but underlying soils remain unfrozen—sometimes through January—because of slow latent heat release. However, because of limited data, zero-curtain methane emissions have been poorly understood.

The new investigation examined soil temperature and methane emissions data from four monitoring sites across the tundra in Alaska's North Slope. One station is located at a National Oceanic and Atmospheric Administration (NOAA) observatory just outside Utqiaġvik, the northernmost city in the United States. There atmospheric methane concentrations in late fall and early winter have been rising above background levels for 2 decades.

The researchers found that from 2001 to 2017, soils froze later, with the zero curtain extending further into winter by about 2.6 days per year. NOAA observatory data suggested that this later freezing was linked to higher above-background methane concentrations in the fall. The team's data also showed that from 2013 to 2017, methane emissions dropped each year after the zero curtain closed.

The findings suggest that later soil freezing may increase methane release from Arctic tundra ecosystems. Because soils remained unfrozen after air temperatures dropped well below 0°C, the researchers concluded that air temperature is a poor predictor of methane emissions. Instead, long-term records of soil temperature could be essential for predicting the effects of climate change on methane release in the tundra. (*Journal of Geophysical Research: Biogeosciences,* https://doi.org/10.1029/2019JG005242, 2019) **—Sarah Stanley,** *Science Writer*

New research suggests that soil temperatures may be far more useful than air temperatures in predicting the effects of climate change on methane emissions from the Alaskan tundra. Credit: Kyle Arndt

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Mountain Communities Face Challenges Worldwide

More than half of the world's population relies on resources from mountain ecosystems, such as timber and water. Rising like islands above the lowlands, mountain systems face unique threats to their sustainability. New research by *Klein et al.* explores these threats on a global scale for the first time, illuminating strategies needed to improve sustainability. The work was led by Mountain Sentinels, a group focused on the sustainability of mountain environments and communities.

The project began with a workshop attended by experts from 12 different mountain systems, each with decades of experience. Working with additional scholars, they identified key facets of mountain systems around the world, including their common characteristics, stressors, paradoxes (such as being rich in resources but poor in income), and benefits to humans. This collaboration enabled the researchers to build a conceptual model of mountain systems.

Herders and their yaks in the Nyainqêntanglha mountain range in central Tibet. Credit: J. A. Klein

The scientists then explored how their conceptual model applies to mountain systems around the world. They surveyed experts from 57 systems across 37 countries, collecting detailed data on land use, stressors, the role of local knowledge, and more. Using this information, they conducted a series of computational analyses to better understand the current state of mountain systems worldwide.

The analysis revealed that many mountain systems face both abrupt threats, such as extreme weather events and economic crises, and gradual threats, such as climate change and policy change. The most widespread threat comes from policies implemented by people who live outside of mountain systems and may lack important local knowledge about the mountain environment.

By categorizing mountain systems according to land use types, such as logging and tourism, the researchers were able to explore the different threats faced by different system types. They found that mountain systems in the developing world where people's livelihoods are subsistence oriented—especially systems that mix agriculture and animal husbandry—are most at risk, despite the many benefits and resources they provide.

These findings point to the complex, cross-disciplinary, and cross-sector efforts necessary to ensure sustainability of Earth's mountain systems. The authors suggest the need for scientists, local stakeholders, and policy makers to collaborate on decisions about what an ideal future looks like for a given mountain system and how best to achieve it. They highlight the importance of filling gaps in knowledge about mountain systems while also addressing poverty and food security. (*Earth's Future,* https://doi.org/10.1029/2018EF001024, 2019) **—Sarah Stanley,** *Science Writer*

Celebrating a Century of Nonlinearity Across the Geosciences

Throughout the 19th and early 20th centuries, the concept of linear systems—in which any changes in output are directly proportional to modifications made to their inputs—dominated the thinking and methodology used to study the physical sciences. Following the end of World War II, however, advances in observational techniques and the development of increasingly powerful computational devices began to alter the way scientists formulate physical problems and solve them mathematically.

During the past half century, these breakthroughs led to a rapid expansion in nonlinear approaches to studying the physical sciences, a development that can only be characterized as revolutionary. The evolution of nonlinear concepts, which describe the cause-and-effect relationships in most natural systems, has significantly increased the range of inquiries geoscientists are able to address. Still, only a small number of nonlinear methodologies in the discipline currently exist, according to a recent paper by *Ghil*.

The author highlights a small selection of key achievements that aptly illustrate the importance of nonlinear concepts in the geosciences. These include novel insights into fluid dynamics, such as the role of multiple large-scale flow patterns in the ocean and atmosphere, which greatly improved long-range weather forecasting; applications related to geophysical turbulence and stochastic dynamical systems; the development of vacillation theory, which led to the theory of strange attractors; and the concept of networks, whose applications include modeling aspects of climate dynamics such as the changes in sea surface temperature patterns associated with the El Niño–Southern Oscillation.

By offering a broad overview of the development and application of nonlinear concepts across the geosciences, the author affords researchers from numerous disciplines an opportunity to reflect on the importance of nonlinearity for understanding geological and geophysical phenomena.

The logical next step, the author argues, is to apply the ideas he presents to the problem of prediction, which will serve as a crucial test of geoscientists' physical and mathematical understanding of the natural world. (*Earth and Space Science,* https://doi.org/10.1029/2019EA000599, 2019) **—Terri Cook,** *Science Writer*

Disappearing Arctic Sea Ice Alters Ecosystems

The Bering Sea has experienced unprecedentedly low winter sea ice levels in recent years. Credit: Artix Kreiger 2, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

In winter 2018, the sea ice extent in the Bering Sea reached the lowest levels observed since 1850, when records began. By late April, warm, southerly winds left sea ice levels at just 10% of the 1981–2010 average for that time of year. In recent research, scientists studied how the unprecedentedly low ice cover affected ecosystems in the region.

As sea ice melts in the spring, it releases fresh water and nutrients into the ocean, seeding phytoplankton blooms that serve as the base of food webs. Researchers call the cascading connections between sea ice cover and the abundance of organisms in ecosystems the oscillating control hypothesis. This process has long been studied in the southeastern Bering Sea, where sea ice levels have contracted or expanded in accordance with multiyear temperature patterns, but not in the northern Bering Sea, which has never experienced a complete lack of winter sea ice.

Springtime ice in the northern stretches of the sea usually keeps ocean bottom temperatures low even at the height of summer, when a "cold pool" typically covers more than 70% of the continental shelf, making the northern reaches cold even when the south is warm. But the northern Bering Sea was not insulated during the winter of 2018, and by the following summer, the cold pool had virtually vanished. The unusual conditions gave *Duffy-Anderson et al.* a chance to find out whether the oscillating control hypothesis might serve as a model for trophic cascades in the northern ecosystem as well.

The researchers used satellite-based measurements of sea ice levels and collected data on ocean temperatures, salinity, oxygen levels, and fluorescence between late April and mid-October 2018. They also took biological samples or biomass estimates of phytoplankton, zooplankton, fish larvae, adult fish, and seabirds.

The team found that the springtime bloom of phytoplankton was delayed and that plankton levels remained low, which led to a low abundance of large zooplankton, though small zooplankton thrived. Samples of larval walleye pollock—one of the world's largest fisheries—indicated that the larval stage of fish was largely unaffected. However, the authors reasoned that the changes in their food supply may still affect the larvae's ability to survive long term. Indeed, estimates of pelagic foragers, including pollock, herring, and capelin, in later stages of development revealed that fish stocks were below average. Observations of seabird colonies indicated smaller populations, decreased reproductive success, and a greater risk of die-off events.

Ultimately, the authors conclude that the cascading ecosystem effects seen in the northern Bering Sea in 2018 were similar to those previously observed in the southeastern region of the sea. They caution that unique aspects of the northern Bering Sea ecosystem, including a different light regime and a northward shift of adult fish populations, could mean that its response won't be exactly the same, however. Still, the model from the southeastern Bering Sea could provide researchers with important insights about what's in store for the northern region in a warming world. And researchers may soon have the opportunity to find out whether the similarities between the regions hold up over the long term, with Bering Sea ice levels nearly reaching record lows again in winter 2019. (*Geophysical Research Letters*, https://doi.org/10.1029/2019GL083396, 2019) **—Kate Wheeling,** *Science Writer*

Atmospheric Sciences

Assistant Professor of Earth, Atmospheric, and Planetary Sciences, Purdue University. The Department of Earth, Atmospheric and Planetary Sciences (EAPS), within the College of Science at Purdue University, invites applications for a tenure-track faculty position in large-scale geophysical fluid dynamics at the rank of Assistant Professor to begin in the 2020-21 academic year.

Qualifications: Candidates must have completed their PhD in Atmospheric Science or related field at the time of employment. Within EAPS and Purdue, candidates will find supportive colleagues and a diverse and vibrant academic community, with ample opportunities for professional and personal growth.

The successful candidate should be able to develop a vigorous, externally funded, internationally recognized theoretical, experimental, and/or observational research program that pursues novel integrative approaches to study geophysical fluid interactions across global-to-regional scales and to develop a complementary teaching portfolio. Possible areas of study may include: planetary-scale modes of climate variability, coupled ocean/atmosphere/cryosphere interactions, stratosphere/troposphere interactions, weather-climate interactions, and predictability in weather and seasonal forecasts.

The candidate's program is expected to complement existing research within the department and teaching needs at the undergraduate and graduate levels. The potential to develop interdisciplinary, collaborative research that cuts across specialty areas within the department, the College of Science, and Purdue's research community is desirable. EAPS has experienced growth in recent years, with 10 new faculty hires in the last three years, and we anticipate further growth in future years. One particular area of emphasis will be in the area of data sciences. We expect synergies between this position and the other hires. In particular, the successful candidate will have multiple opportunities to join transdisciplinary efforts in areas such as natural hazards risk prediction, fusion of modeling and data science, and the food-energy-water nexus.

The College: EAPS is part of the College of Science, which comprises the physical, computing and life sciences at Purdue. It is the second-largest college at Purdue with over 350 faculty and more than 6000 students. With multiple commitments of significant investment and strong alignment with Purdue leadership, the College is committed to supporting existing strengths and enhancing the scope and impact EAPS. These positions are a central component of a large-scale interdisciplinary hiring effort across key strategic areas in the College, including mathematical and computational foundations, quantum computation, and data science, and aligns with the new campus-wide key strategic priority declared by Purdue's Board of Trustees including the Integrative Data Science Initiative (see https://www.purdue.edu/data-science/). Purdue itself is one of the nation's leading land-grant universities, with an enrollment of over 41,000 students primarily focused on STEM subjects. For more information, see https://www.purdue.edu/purduemoves/initiatives/stem/index.php.

Application Procedure: Interested applicants should apply at https://career8.successfactors.com/sfcareer/jobreqcareer?jobId=7960&company=purdueuniv&username=, and submit: 1) a curriculum vitae, 2) a research statement, 3) a teaching statement, and 4) complete contact information for at least 3 references.

Purdue University's Department of Earth, Atmospheric, and Planetary Sciences is committed to advancing diversity in all areas of faculty effort, including: scholarship, instruction, and engagement. Candidates should address at least one of these three areas in their cover letter, indicating their past experiences, current interests or activities, and/or future goals to promote a climate that values diversity and inclusion.

Review of applications will begin January 6, 2020 and continue until the position is filled. Questions related to this position should be sent to Matthew Huber (eaps-faculty-search@purdue.edu). A background check will be required for employment in this position. Purdue University is an ADVANCE institution.

Purdue University is an EOE/AA employer. All individuals, including minorities, women, individuals with disabilities, and veterans are encouraged to apply.

Visiting Research Scientists, Princeton University. In collaboration with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), the Atmospheric and Oceanic Sciences Program at Princeton University solicits applications to its Visiting Research Scientist Program funded by the Cooperative Institute for Modeling the Earth System (CIMES).

The AOS Program and GFDL offer a stimulating environment with significant computational and intellectual resources in which to conduct collaborative or independent research. Independent researchers and more senior scientists who wish to visit GFDL for the purpose of collaboration, for sabbatical or short visits, will be considered for partial support. We seek applications in all areas of earth system science within the three research themes of CIMES: 1) Earth System Modeling; 2) Seamless prediction across time and space scales; 3) Earth System Science: Analysis and Applications.

Further information about the Program may be obtained from: http://aos.Princeton.edu/. Applicants are strongly encouraged to contact potential hosts at GFDL and Princeton University prior to application to discuss areas of possible research.

Complete applications, including a CV, copies of recent publications, three letters of recommendation, and a research proposal including the project title, should be submitted by December 15th, 2019 for full consideration. Applicants must apply online to https://www.Princeton.edu/acad-positions/position/14242. Advanced degree is required. We would like to broaden participation in earth system science and therefore encourage applications from groups historically under-represented in science.

Princeton University is an equal opportunity 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.

Earth and Space Science Informatics

Berkeley Lab's Energy Geosciences Division has an immediate opening for a Staff or Senior Scientist in Applied Geophysics. We are seeking an Applied Geophysicist with a record of leading innovative research in characterizing subsurface structure, and monitoring properties and processes, with a focus on seismology. As a member of the Energy Geosciences Division (EGD) you will lead and participate in leading-edge research in passive and active seismic methodologies, including borehole data acquisition. A successful candidate is expected to lead and expand our historically vibrant and extramurally supported frontier research program in applied seismology with a broad range of support from U.S. DOE programs in geothermal, carbon storage, and oil and gas, as well as external industry funding. Continued focus on developing novel field methods is expected, with an emphasis on permanent reservoir monitoring and time-lapse seismic imaging approaches. Development of novel imaging and inversion methods is encouraged, and internal collaboration with non-seismic methods including electromagnetic acquisition and imaging is also expected.

Currently funded research areas include distributed acoustic sensing (DAS), continuous active-source seismic monitoring (CASSM) using both surface and borehole sources, and advanced microseismic monitoring, as well as the development of new seismic modeling and inversion techniques. Data acquisition research areas utilize dedicated engineering support from LBNL's Geoscience Measurement Facility which houses extensive resources for novel field seismic acquisition systems, including high-temperature wireline instruments, downhole tools, recording systems, and fiber optics. This is in addition to more traditional geophysical instrumentation, experienced field personnel, and instrument fabrication facilities.

As part of EGD's 'Sustainable Earth' Strategic Direction, these methods will be utilized in a variety of contexts relevant to DOE's mission of finding scientific solutions for the sustainable utilization of the subsurface, including characterization and monitoring of geological carbon storage, geothermal systems, oil and gas reservoirs, nuclear waste disposal, and groundwater management. The successful candidate will take advantage of world-class experimental and computational facilities at Berkeley Lab, including LBNL's unique Geosciences Measurement Facility to propose and develop funding for projects in both current and new research areas. Active collaboration with other scientific divisions across Berkeley Lab including the Climate and Ecosystem Sciences division, as well as UC Berkeley, is expected.

To apply, please visit us at http://50.73.55.13/counter.php?id=169828 and follow the on-line instructions to complete the application process.

Postdoctoral Fellow (ESS-DIVE Project)–88042. Organization: GO-Energy Geosciences

Berkeley Lab's Earth and Environmental Sciences Area (EESA) has an opening for a Postdoctoral Fellow to join the Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE) project. ESS-DIVE is a DOE data repository that stores diverse datasets from terrestrial and subsurface ecosystem research projects.

The postdoc will join the ESS-DIVE research and development team working on community engagement, data standards and building tools for data use.

What You Will Do:

- Research and provide recommendations on community standards for environmental data.
- Work with the community to adopt existing standards or define new standards as needed.
- Build file parsers, quality checkers and other tools to enable advanced search, integration and visualization of data submitted in standardized formats.
- Collaborate extensively with the DOE Environmental Systems Science (ESS) research community.

We are seeking candidates with strong communication skills who have prior experience in environmental data synthesis/analysis and scientific programming.

For full description and to apply please visit: http://50.73.55.13/counter.php?id=170695

Geochemistry

Robert Nathan Ginsburg Chair in Marine Geosciences. The Rosenstiel School of Marine and Atmospheric Sciences requests applications for the Robert Nathan Ginsburg Endowed Chair in Marine Geology. Although applicants are encouraged in all fields of the Marine Geology, we are particularly interested in scientists in the field of sedimentology, conducting research in the modern to unravel processes in forming or distributing carbonate sediments. Candidates for this position are expected to develop a vigorous, externally funded field and laboratory research program, supervise graduate students, and participate in the teaching mission of the Department and the School at both the graduate and undergraduate levels and interact with current faculty. In particular, the candidate will play a major role in the Comparative Sedimentology Laboratory – Center for Carbonate Research established by Robert Ginsburg. The appointment is expected to be made at the Professor level, but we will consider applications from motivated and energetic younger scientists for appointment at the rank of Associate Professor.

The University of Miami offers a unique tropical location adjacent to major modern carbonate environments and the opportunity to integrate biological and physical oceanographic expertise into process-oriented sedimentological research through collaboration with faculty in the Departments of Marine Biology and Ecology and Ocean Sciences. More details of the faculty and opportunities within the Department of Marine Geosciences can be found at https://marine-geosciences.rsmas.miami.edu/index.html.

Interested applicants should contact Professor Peter K. Swart, Department of Marine Geosciences, RSMAS/University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149 (pswart@rsmas.miami.edu).

Applications will only be accepted electronically at mgssearch@rsmas.miami.edu. The position will remain open until filled. Ideally, we would like the successful candidate to be in place by September 2020.

The University of Miami is an equal opportunity employer.

Geodesy

Assistant Professor – Remote Sensing Geoscience. The Department of Geology in the School of Earth, Society, and Environment (https://earth.illinois.edu/) at the University of Illinois at Urbana-Champaign, the flagship campus of the University of Illinois System, seeks an outstanding scholar with expertise in Remote Sensing. Applications are invited from candidates whose research falls within the broad scope of Earth sciences – including, but not limited to: surface and groundwater, landscape change, tectonics, environmental and climate science, earthquakes, glaciology, and volcanology. The full-time, 9-month (academic year) tenure-track faculty appointment is at the Assistant Professor level with a target start date of August 16, 2020.

The Department of Geology resides within the College of Liberal Arts and Sciences, a world leader in research, teaching, and public engagement. Faculty in the College create knowledge, address critical societal needs through the transfer and application of knowledge, and prepare students for lives of impact in the state, nation, and globally. To meet these objectives, the College embraces and values diversity and difference through hiring faculty candidates who can contribute through their research, teaching, and service to the diversity and excellence of the Illinois community.

The University of Illinois is an Equal Opportunity, Affirmative Action employer. Minorities, women, veterans and individuals with disabilities are encouraged to apply. For more information, visit http://go.illinois.edu/EEO.

The University of Illinois is committed to the family needs of our faculty members, including dual career partners. The Dual Career Academic Couples program, Provost Initiative #8, facilitates the placement of tenure-system faculty partners in positions on campus (including tenure track). More information may be found at: https://provost.illinois.edu/policies/provosts-communications/communication-8-dual-career-academic-couples-program/

The Geology Department is committed to building and maintaining an excellent and diverse academic environment. We are dedicated to advancing inclusion and diversity through our teaching, research, and service. Qualified applications will be considered regardless of age, race, religion, color, sex, gender identity, sexual orientation, national origin, disability, or protected veteran status.

Responsibilities in Research and Teaching: The successful candidate will establish and maintain an externally funded and independent research program in the area of remote sensing. The successful candidate will be expected to teach at least two courses within the Geology curriculum at the undergraduate and graduate levels.

Synergy with Campus Excellence Themes and Strengths: The successful candidate will benefit from existing strengths within the Department of Geology: surface environments and landscape research, tectonics, geophysics, geodynamics; within SESE: CyberGIS & geography, and Atmospheric Remote Sensing; and across campus: the National Center for Supercomputing Applications, data science programs in Computer Science and Electrical & Computer Engineering, and fluid dynamic, surface environments and earthquake hazards research in Civil and Environmental Engineering, and Mechanical Science and Engineering. Excellent opportunities also exists for collaborations with the United States Geological Survey and Illinois State Geological Survey.

Qualifications: Ph.D. or equivalent international degree in Geology or a related field by mid-June 2020 for a preferred start date of Aug 16, 2020. Applicants must have a promising research agenda and a strong commitment to undergraduate and graduate teaching.

Candidates with superior qualifications who will complete all the Ph.D. requirements within the first appointment year may be appointed at the rank of Instructor. After the Ph.D. requirement is met, the appointment will be changed to Assistant Professor.

Salary and Benefits: Salary is competitive, commensurate with skills and experience. Information on benefits may be found at: https://www.hr.uillinois.edu/benefits/

Application: To apply, create your candidate profile through https://go.illinois.edu/GEOLOGYfaculty and submit application materials by November 15, 2019. Required documents:

- Cover letter that details suitability for and interest in the position
- Curriculum Vitae
- Up to three representative publications
- Statement of Research Interests
- Statement of Teaching Experience and Goals
- Statement on Advancing Diversity and Inclusion
- Contact information for three professional references. Letters of recommendation may be requested electronically from referees at a later date.

Only applications submitted through the University of Illinois Job Board will be considered. Questions can be directed to search committee chair Prof. Lijun Liu, ljliu@illinois.edu, phone: (217) 333-3540.

The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer.

Hydrology

Assistant Professor, Ohio State University. The School of Earth Sciences (SES) and the School of Environment and Natural Resources (SENR) in partnership with the Sustainability Institute seek an ecohydrologist, broadly defined, to complement existing expertise and foster collaboration among these partners at the Assistant Professor level (9-month, tenure-track position). We welcome applicants across a wide range of expertise that intersect with ecological and hydrological systems. Scientific research themes could range from urban to remote environments, ecosystems and biogeochemical cycling across a variety of scales, and/or the effects of climate or other stimuli on these systems. Methodological emphasis could range from sensor technologies on remote platforms (aircraft, drones, or satellite) to sensor networks, from mathematical/statistical to experimental/observational approaches, and from simple to complex systems including coupled natural-human systems. This position is affiliated with the Sustainability Institute, which supports interdisciplinary research on sustainability and resilience topics. Candidates with a PhD in an ecohydrology relevant field, or candidates who have completed all requirements but their dissertation may apply. As a campus with a continuously growing diverse student body, we encourage applications from women and under-represented minorities. Demonstrated experience in inclusive pedagogy and in mentoring members of underrepresented groups is desirable. The Ohio State University is committed to establishing a culturally and intellectually diverse environment, encouraging all members of our learning community to reach their full potential. We are responsive to dual-career families and strongly promote work-life balance to support our community members through a suite of institutionalized policies. The complete job advertisement is available at: https://academicjobsonline.org/ajo/jobs/14781

Interdisciplinary

Assistant Professor of Earth System Science (tenure track): Hydrological and Climate Extremes. The Department of Earth System Science (ESS) at the University of California, Irvine invites applications for a tenure-track faculty position focused on the predictive understanding of changing hydrological and climate extremes. These

Department of Geosciences
PRINCETON UNIVERSITY

HARRY HESS FELLOWS PROGRAM

The Department of Geosciences at Princeton University announces competition for the 2020-2021 **Harry Hess Fellows Program.** This honorific postdoctoral fellowship program provides opportunities for outstanding geoscientists to work in the field of their choice. Research may be carried out independently or in collaboration with members of the Geosciences Department. One or more Hess Fellows may be appointed. Applicants must expect to have earned a Ph.D. at the time of the start of the fellowship, but not more than five years before. Current areas of research include:

- Biogeochemical Cycles
- Environmental Chemistry
- Isotope Geochemistry
- Glaciology
- Geomicrobiology
- Mineral Physics
- Oceanography
- Geochronology
- Paleoclimatology
- Paleontology
- Petrology
- Seismology
- Tectonics
- Atmospheric Science
- Planetary Science
- Earth History

Applications are due on **December 15th, 2019** but evaluation of applications and interviews of candidates will begin immediately. Applicants should include a cover letter, a curriculum vitae including a publication list, a 1-2 page statement of research interests and goals, and name, address and email address of three referees familiar with their work by applying on the Princeton University jobsite at **https://www.princeton.edu/acad-positions/position/13961.** Hess Fellowships provide a competitive annual salary, depending upon experience, along with a significant allowance for travel to meetings and for research support. Initial awards are for one year, with the possibility of renewal depending upon satisfactory performance and available funding, at the rank of Postdoctoral Research Associate. A preferred starting date is on or before **September 1st, 2020.**

This position is subject to the University's background check policy. Princeton University is an equal opportunity employer/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.

Information about the research activities of the Department of Geosciences may be viewed at **https://geosciences.princeton.edu**.

extremes are unusual events that inflict disproportionate damage to ecosystems and society including floods, droughts, heat waves, cold extremes, hurricanes, atmospheric rivers, wildfires, and intense air pollution episodes. Identifying the contribution of climate change to the frequency, intensity and behavior of individual events, as well as the aggregated statistics of multiple events, is a field of science that is increasingly shaping the public's perception of climate change. We welcome applications from researchers who are using a range of approaches, including observational analysis, dynamical theory, machine learning, statistical modeling, and dynamical and fully coupled Earth system models to study changing hydrological and climate extremes, with an emphasis on creating new knowledge about the basic mechanisms that will enable a predictive understanding of these phenomena and their impacts on human and natural systems.

UC Irvine's ESS department was founded to explore the global environmental changes that occur on human time scales. The department has 24 full time faculty from diverse backgrounds (http://www.ess.uci.edu/). The successful applicant will have a strong research agenda, a commitment to excellence in teaching and in promoting diversity and inclusion in a collegial, cross-disciplinary department.

The University of California, Irvine is an Equal Opportunity /Affirmative Action Employer and strives to be a national leader and global model of inclusive excellence (https://inclusion.uci.edu/). UCI is a Hispanic-Serving Institution (HSI) and an Asian American and Native American Pacific Islander-Serving Institution (AANAPISI). We seek faculty who are committed to diversity as well as diverse faculty who will be role models for our students. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability, age, protected veteran status, or other protected categories covered by the UC nondiscrimination policy. A recipient of an NSF ADVANCE award for gender equity, UCI is responsive to the needs of dual career couples, supports work-life balance through an array of family-friendly policies, and is dedicated to broadening participation in higher education. Compensation is competitive, and includes priority access to purchase on-campus faculty housing at below-market prices. The area offers numerous recreational and cultural opportunities, and one of the highest-ranked public school systems in the nation.

Candidates must have a doctoral degree. Apply online at https://recruit.ap.uci.edu/JPF05780 or contact facultysearch@ess.uci.edu. Review of applications will begin January 2, 2020.

Assistant Professor of Environmental Science. The University of Virginia College and Graduate School of Arts & Sciences Department of Environmental Sciences invites applicants for a tenure-track Assistant Professor position in Hydroclimatology. We seek candidates who are passionate about research and teaching in a world-class institution. The position in hydroclimatology bridges atmospheric sciences and hydrology, two core areas of our department. This research area focuses on interactions between weather and climate and the hydrological cycle over regional to global scales. We wish to hire a scientist who will thrive in an interdisciplinary department.

In addition to developing external funding to support research endeavors, candidates will be expected to teach at the graduate and undergraduate levels and provide service to the University, Department, and professional organizations.

Qualifications:

Applicants must hold a Ph.D. at the time of appointment. Successful candidates would be expected to teach the introductory course for undergraduate majors in either atmospheric sciences or physical hydrology, along with upper-level undergraduate and graduate courses in the candidate's areas of expertise.

Application Process:

Please apply online at https://uva.wd1.myworkdayjobs.com/en-US/UVAJobs/job/Charlottesville-VA/Assistant-Professor-of-Environmental-Science_R0010711 and attach a cover letter, research statement, teaching statement, curriculum vitae, and contact information for three references. The cover letter should include (1) a summary of how the applicant's research experience fits in the general area of Hydroclimatology, (2) a summary of how the applicant meets the stated qualifications, and (3) any demonstrated past experience working on issues of diversity, equity and inclusion and/or working with diverse populations.

Application Deadline:

Review of applications will begin November 15, 2019; however, the position will remain open until filled. The appointment start date will begin August 25, 2020. The University will perform background checks on all new hires prior to employment.

Questions regarding the application process should be directed to: Rich Haverstrom, Faculty Search Advisor, at rkh6j@virginia.edu

For information on the benefits available to members of the academic faculty at UVA, visit hr.virginia.edu/benefits.

UVA assists faculty spouses and partners seeking employment in the Charlottesville area. To learn more please visit https://dualcareer.virginia.edu/ For more information about UVA and the Charlottesville community please see http://www.virginia.edu/life/charlottesville and https://embarkcva.com/.

The University of Virginia, including the UVA Health System and the University Physician's Group are fundamentally committed to the diversity of our faculty and staff. We believe diversity is excellence expressing itself through every person's perspectives and lived experiences. We are equal opportunity and affirmative action employers. All qualified applicants will receive consideration for employment without regard to age, color, disability, gender identity, marital status, national or ethnic origin, political affiliation, race, religion, sex (including pregnancy), sexual orientation, veteran status, and family medical or genetic information.

Faculty Position–Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan. The Department of Atmospheric Sciences at National Taiwan University seeks two to four faculty members in the areas of weather, climate and earth system, or atmospheric physics and chemistry, at the Assistant, Associate or Full Professor levels. Applicants should have a Ph.D. degree, preferably with postdoctoral experience, cross-discipline research capability, and teaching experience. The position will begin in August 2020. Application should be submitted through the Academic Jobs Online by including (1) curriculum vitae including publication list, (2) statement of research interests, and (3) statement of teaching experience and interests. The applicant should also arrange three letters of reference that sent directly from the recommenders. All application material should be submitted by December 31th, 2019.

Related website: https://academicjobsonline.org/ajo/jobs/14121

Faculty Search Committee

Department of Atmospheric Sciences,

National Taiwan University,

No.1, Section 4, Roosevelt Road,

Taipei 106, Taiwan

E-mail: minhuilo@ntu.edu.tw

HARC seeks a Program Director/Senior Research Scientist, Climate Risk in Urban & Coastal Systems.

Department: Research Operations

Office/Group: ENV

Reports to: President

GENERAL PURPOSE OF JOB

The Program Director, Climate Risk in Urban and Coastal Systems, is responsible for developing this new program area, leading programmatic business development activities, managing research teams, and performing basic or applied research and policy research support in support of HARC's mission. Work will involve a high degree of expertise, creative insight, and technical skill in assessing climate risk for urban and/or coastal systems and the ability to work with experts in the other related disciplines. Work may involve the development of new practices, technology and methodologies and will include directing the operation of a research program by performing the following duties.

ESSENTIAL DUTIES AND RESPONSIBILITIES include, but are not limited to, the following.

Major Duties

- Shape the content of HARC's mission-driven research, fundraising and grantsmanship efforts, meeting both longer-term strategic goals and shorter-term commitments to funders and partners.

• Develop and manage a programmatic team; creating and supporting a high-performance, collaborative and inclusive working environment where staff can realize professional growth and success.

• Lead a team to plan and model climate risks, effects of regional climate mitigation and adaptation strategies.

• Lead a team to connect high-resolution climate data and projections to regional issues, environmental stressors and critical infrastructure (e.g. ports, industry and transportation).

• Plan, direct and perform complex research and investigations pertaining to climate risk, resilience and adaptation in coastal cities with a focus on the intersections with environmental stressors and community well-being.

• Successfully develop and secure funding for program initiatives from philanthropic, government, and private sector sources.

• Develop and maintain relationships with potential funding organizations, partners and media entities to promote efforts.

• Effectively communicate identified needs, plans and results to private sector, policy-makers, environmental organizations and the public.

• Other duties may be assigned.

Proposal and Business Development

• Take a leadership role in HARC's mission-oriented, programmatic development.

• Identify and develop new funding sources and funder relationships.

• Write white papers and proposals for submission to funding sources.

Project Management

• Plan and execute or manage research or technology development; manage project teams, budgets, and timely completion of project deliverables.

• Develop collaborations with external partners and serve as a research leader in the Greater Houston region.

• Responsible for the management of one or more project teams.

Internal Collaboration

• Initiate and promote teamwork, shared learning and integrated approaches to sustainability.

• Develop multi-disciplinary projects and team in partnership with other HARC supervisors.

• Supervise the activities of other personnel and serve as an in-house mentor.

• Advise executive management.

• External Outreach and Engagement

• Operate a well-established professional network with the ability to communicate and develop interpersonal relationships in stakeholder communities.

• Represent HARC to external political and community leaders/staff, media contacts, partners and public audiences at conferences, meetings, and through written materials.

• Make contributions to discipline through scientific literature and conference presentations; maintain broad knowledge of state-of-the-art principles, theories and practices in scientific discipline.

QUALIFICATIONS

To perform this job successfully, an individual must be able to perform each essential duty satisfactorily. The requirements listed below are representative of the knowledge, skill, and/or ability required. Reasonable accommodations may be made to enable individuals with disabilities to perform the essential functions.

Education and Experience

Ph.D. in atmospheric/oceanic/climate science, engineering, geography, geosciences or a related field with a minimum of 12 years of experience leading multi-disciplinary research teams and developing funded research initiatives; or an M.S. in above disciplines with a minimum of 16 years' experience. Experience with a mix of private and public sector, project-based environments including project development, university research, consulting, or professional services is preferred.

Program Management Abilities

The ideal candidate will have a strong creative and entrepreneurial spirit and a proven ability to find new and impactful approaches, navigate obstacles, and influence others' thinking to achieve impact beyond one's own activities. Must be able to design work flows, pro-

FM Global

RESEARCH SCIENTIST- FLOOD

FM Global is a leading property insurer of the world's largest businesses, providing more than one-third of FORTUNE 1000-size companies with engineering-based risk management and property insurance solutions. As a leader in property loss-prevention, FM Global has been on the forefront of innovation since 1835 paving the way for many insurance industry firsts. Exciting and interesting technical challenges await you when you join a world-class research team dedicated to reducing the impact of natural hazards.

As part of our research division, you'll work alongside a unique group of scientists across engineering, earth, hydrological, and atmospheric sciences to protect the value of FM Global's clients' businesses by developing methods to identify hazards, assess risk, and produce loss prevention solutions that are efficient and cost-effective.

We have openings for planning and conducting research on flood, and subsequent property losses. Positions require a PhD degree. Candidates are expected to have some or all of:
• a research record in one or more areas related to riverine or coastal flood modeling, hydrodynamics, hydrology, precipitation or related field;
• a broad physical understanding of flood modeling processes and demonstrated experience using and combining large data sets in various formats;
• deep knowledge of modeling principles, and model setup, calibration and evaluation;
• proven technical programming experience and numerical analysis skills;
• solid background in probability and statistics; and
• GIS skills.

Previous experience with experimental work is a plus. Project management abilities and excellent written and verbal communication skills are required. The job title depends on qualifications and experience.

Interested candidates, please send your resume to **Tiara.Adducie@fmglobal.com** (Human Resources), or through our careers page at:
http://jobs.fmglobalcareers.com/careers/research-jobs

IRIS

PRESIDENT, THE INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY (IRIS)

The Incorporated Research Institutions for Seismology (IRIS) invites applications and nominations for the next **President of the Consortium.** The President is the public face of IRIS and represents the Consortium through leadership and management activities with the geosciences community, federal agencies, partners, and member institutions.

Founded in 1984 with support from the National Science Foundation (NSF), IRIS is a consortium of 125 U.S. universities dedicated to advancing research and education in seismology to understand our dynamic planet and to benefit society. IRIS programs contribute to new discoveries within our planet, natural hazard mitigation, national security, environmental monitoring, advances in geo-computation, networking and communications, and in building a scientifically and technologically proficient workforce. The IRIS membership comprises virtually all U.S. universities with research programs in seismology and includes a growing number of Educational Affiliates, U.S. Affiliates, and Foreign Affiliates. IRIS management is currently headquartered in Washington, DC, but IRIS facilities are distributed internationally and operated in cooperation with the U.S. Geological Survey and other partner organizations and institutions. IRIS has annual revenues of approximately $30 million, and the Consortium employs roughly 53 full-time professional staff.

Candidates for the President position will have significant management experience as well as a background in leading complex research or facilities programs in academia, related government agencies, or industry. Candidates should be able to collaborate and negotiate strategically with other scientific and educational facilities and organizations. This is particularly critical at this time given NSF's 2019 decision to support a single seismic and geodetic facility starting in 2023. The ideal candidate will have a PhD in Earth Science, or equivalent professional expertise, along with experience in the administration of federal awards, a comprehensive understanding of federal funding structures and requirements, and an ability to identify and pursue new and diverse funding sources.

The President should be a dynamic leader who is able to communicate effectively with the IRIS community, federal agency leadership, and other sponsors and scientists. The ideal candidate will have a demonstrated record of successful scientific and administrative leadership and be able to proficiently engage with and build consensus across the geophysical community. The President will be capable of vision, planning, and executive management in partnership with the governing IRIS Board of Directors. Candidates must promote and embrace diversity and inclusion, global awareness, and ethical values.

A more in-depth position description may be found at **https://www.iris.edu/hq/employment/job/president1**.

Requests for additional information should be directed to Professor Charles J. Ammon, Chair, IRIS President Search Committee, **hr@iris.edu**. Applications should include a full vita; a statement describing the applicant's vision for IRIS for the immediate term and for the period beyond the 2023 expiration of the current SAGE2 cooperative agreement; a statement addressing past and/or potential contributions to diversity, equity, and inclusion; and the names and contact information of three references. Applications and nominations will be accepted until a new President is selected. For optimal consideration, interested parties are encouraged to apply by **15 December 2019** at the address below.

Presidential Search Committee c/o IRIS
1200 New York Avenue, NW
Suite 400
Washington, DC 20005

The IRIS Consortium believes a diverse staff makes us a stronger organization. We are committed to hiring people of all ages, races, ethnicities, genders, sexual orientation or gender identities, marital status, veteran status, religions, and disabilities. All qualified candidates are encouraged to apply.

POSITIONS AVAILABLE

cedures, track progress, report progress, and discern results. Must be able to identify and resolve problems in a timely manner. Must be able to successfully identify alternatives and implement change when deemed appropriate. Must be able to assess program team's strengths/weaknesses/opportunities and take appropriate action. Must be able to influence outside organizations that are working on similar programs, motivate subcontractors and ensure that they meet deadlines and accomplish the appropriate tasks. Also, must be able to influence industry, regulators, policy makers, others. The successful candidate should be considered a respected authority in their field. The ideal candidate will effectively balance team and individual responsibilities; work well in a collaborative environment as well as independently. Maintains confidentiality. Meets commitments on time and within budget. Able to develop strong business relationships.

Data Analysis and Computing Abilities

Experience in data analytics, visualization, statistics, modeling and other advanced computer science techniques is a plus. Ability to define problems, collect data, establish facts, and draw valid conclusions. Ability to interpret an extensive variety of technical instructions in mathematical or diagram form and deal with several abstract and concrete variables.

Communication and Writing

Strong communication skills with demonstrated experience developing technical reports, peer-review publications and proposals. Ability to communicate complex technical findings in a succinct and easy-to-understand manner using captivating language meant to engage the public. Must have demonstrable skills in problem solving and critical thinking.

Supervisory Abilities

Collegial, mission-driven team leader with well-developed interpersonal skills and experience managing teams of 5 or more through periods of change. Directly supervises employees based on program needs. Carries out supervisory responsibilities in accordance with the organization's policies and applicable laws. Responsibilities include interviewing, hiring, and training employees; planning, assigning, and directing work; appraising performance; rewarding and disciplining employees. Delegates work assignments and gives authority to work independently. Sets expectations and monitors delegated activities. Develops subordinates' skills and encourages professional growth.

Outreach and Engagement Abilities

Strong outreach and fundraising capabilities; speaking and writing to business and donor audiences; demonstrated capability to present ideas to companies and funders. Accomplished public speaker. Ability to read, analyze, interpret and synthesize scientific and technical reports, financial reports, and legal documents. Able to handle media inquiries and engage non-technical audiences. Must have excellent verbal and nonverbal communication skills. Writes clearly and informatively.

Work Environment

Desire to work in a fast-paced, collaborative, creative environment, and ability to move across and work on several projects at once. Some travel may be involved based on project activity but no more than 20% of time. Directors have opportunity for flexible work locations based on project needs. To perform this job successfully, an individual must be computer literate in word processing, spreadsheet, internet and email software as well as project specific software.

Physical Demands

The physical demands described here are representative of those that must be met by an employee to successfully perform the essential functions of this job. Reasonable accommodations may be made to enable individuals with disabilities to perform the essential functions. The employee must occasionally lift and/or move up to 20 pounds. Specific vision abilities required by this job include close vision. While performing the duties of this job, the employee is frequently required to sit and talk or hear. The employee is occasionally required to stand; walk; use hands to finger, handle, or feel and reach with hands and arms.

Ph.D. Positions in Earth System Science. https://vimeo.com/260928738

https://www.clarku.edu/departments/geography/graduate-programs/doctoral-programs/

Applications are invited for Ph.D. assistantships within the Graduate School of Geography at Clark University. Ph.D. admission covers tuition, provides an annual stipend, and includes eligibility for competitive fellowships. Clark's Earth System Science program features expertise in terrestrial ecosystems and global change, hydrology, forest ecology, biogeography, polar science, terrestrial and marine biogeochemistry, disturbance and landscape ecology, GIScience, and remote sensing. All accepted Ph.D. applicants receive guaranteed TA/RA stipends.

The Graduate School of Geography at Clark University is internationally renowned for innovative scholarship and is an acknowledged leader in the field. Consistently ranked as one of the top-ten geography graduate programs by the National Research Council, Clark Geography enables graduate students to train with top professionals and participate in a world-class research community. Students are guaranteed tuition remission and Graduate Assistantships for a minimum of four years, fostering a tight-knit, supportive intellectual community. Having awarded more Ph.D.s than any other geography program in the U.S., Clark Geography has a reputation for training future leaders in the field.

Applications are due December 31, 2019 for Fall 2020 program entry. For complete details see our website (www.clarku.edu/departments/geography), or contact Rachel Levitt, RLevitt@clarku.edu , 508-793-7282.

Postdoctoral/Research Scientists, Princeton University. In collaboration with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), the Atmospheric and Oceanic Sciences Program at Princeton University solicits applications to its Postdoctoral Research Scientist Program funded by the Cooperative Institute for Modeling the Earth System (CIMES).

The AOS Program and GFDL offer a stimulating environment with significant computational and intellectual resources in which to conduct collaborative or independent research for the modeling, understanding and predictability of the Earth System from weather to centennial time scales. We primarily seek applications from recent Ph.D.s for postdoctoral positions but will accept applications from more experienced researchers. Appointments are made at the rank of Postdoctoral Research Associate or more senior initially for one year with the possibility of renewal for a second year based on satisfactory performance and continued funding. A competitive salary is offered commensurate with experience and qualifications.

We seek applications in all areas of earth system science within the three research themes of CIMES: 1) Earth System Modeling; 2) Seamless prediction across time and space scales; 3) Earth System Science: Analysis and Applications. The broad scope is improved representation of processes in models, high-resolution modeling, and advancing the understanding of the Earth System including its variations, changes, and sensitivity. Current areas of particular interest are: Stratospheric chemistry and volcanic aerosols; Ice and mixed-phase cloud microphysics; Aerosol-cloud-precipitation-radiation interactions; Lower atmosphere-surface interactions over land and ocean; Ocean dynamics and its role in climate and ocean ecosystems; Subseasonal to seasonal predictions of high-impact weather events; Decadal projections of regional climate and extremes using large high-resolution climate model ensembles; Detection and causal attribution of climate; applications of novel machine learning methods; Statistical downscaling and bias correction of model simulations.

Further information about the Program may be obtained from: http://aos.Princeton.edu. Applicants are strongly encouraged to contact potential hosts at GFDL and Princeton University prior to application to discuss areas of possible research.

Complete applications, including a CV, copies of recent publications, three letters of recommendation, and a research proposal including the project title, should be submitted by December 15th, 2019 for full consideration. Applicants must apply online to https://www.Princeton.edu/acad-positions/position/14241. We would like to broaden participation in earth system scientific research and therefore encourage applications from groups historically underrepresented in science. These positions are subject to the University's background check policy.

Princeton University is an equal opportunity 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.

Associate Director, Environmental Division, Bureau of Economic Geology. The Bureau of Economic Geology (Bureau) in the Jackson School at The University of Texas at Austin seeks a highly talented individual to lead its Environmental Research Division.

Responsibilities

- Serve as part of a small, integrated administrative team of Directors
- Set vision for and manage and grow the Environmental Division staff of approximately 50 staff
- Create and pursue a vision for multidisciplinary environmental research
- Work with Principal Investigators (PI's) to develop sources of funding for existing and new multidisciplinary programs in the areas of sustainable water resources, coastal geology, natural hazards, induced and naturally occurring earthquakes, carbon sequestration, and geologic mapping
- Build relationships with global federal and state agencies, industry, foundations, NGOs, and international groups that will ensure that new program opportunities are created and funded
- Manage staffing and scheduling; coordinate with administrators and project PI's to ensure that projects are on schedule, on budget, and research groups are collaborating appropriately
- Represent the Bureau at conferences and UT meetings.

Required Qualifications

Advanced degree with major course work in the field of earth science. Ph.D. with minimum of 12 years work experience, or Masters's degree with minimum 17 years experience, in a field related to the Bureau's core areas of environmental research, as per responsibilities outlined above. Excellent management, administrative, leadership and organizational abilities. Previous experience as a successful leader of major research programs. Acknowledged contributions in one or more aspects of environmental research. Relevant education and experience may be substituted as appropriate.

Preferred Qualifications

Proven record of research and leadership, preferably related to the Bureau's core areas of environmental research. Demonstrated ability to attract and administer external funds from a variety of sources, including federal agencies, state and local governments, and industry. A strong record of research publication and presentations. Evidence of innovation and ability to think creatively. Salary Range: $180,000 + depending on qualifications

About the Bureau of Economic Geology

Established in 1909, the Bureau of Economic Geology in the Jackson School of Geosciences is the oldest and second-largest organized research unit at The University of Texas at Austin. The Bureau is the State Geological Survey of Texas, and conducts basic and applied research around the world focusing on the intersection of energy, the environment, and the economy. The Bureau partners with federal, state, and local agencies, academic institutions, industry, nonprofit organizations, and foundations to conduct high-quality research and disseminate the results to the scientific and engineering communities as well as to the broad public. The Bureau provides technical, educational, and publicly accessible information via a myriad of media forms to Texas, the nation, and the world.

Talented people are the Bureau's formula for success. Our staff of over 250 includes scientists, engineers, economists, graduate students and support staff, representing 27 countries, often working in integrated, multidisciplinary research teams. The Bureau's facilities and state-of-the-art equipment include more than fifteen individual laboratories hosting researchers investigating everything from nanoparticles to basin-scale phenomena.

To apply and for more information, please go to https://utaustin.wd1.myworkdayjobs.com/UTstaff/job/PICKLE-RESEARCH-CAMPUS/Program-Director_R_00006402. The search will remain open until filled. Please direct queries to the search committee chair, Mark Shuster at recruiting@beg.utexas.edu.

Savannah River National Laboratory Physical Hydrologist. The Savannah River National Laboratory is seeking versatile and highly motivated candidates to provide technical leadership for the surface water modeling and assessment program within the Atmospheric Technologies Group (ATG). The ATG conducts applied research and technology development in meteorology and surface water hydrology at the U. S. Department of Energy's Savannah River Site in South Carolina. ATG's clients include the DOE and other U. S. government agencies with interests in national security, international nuclear nonproliferation, and emergency response.

The successful candidate will be expected to lead the ongoing development and application of advanced in-house models for predicting hydrodynamic flows and the resulting fate and transport of waterborne contaminants and their impacts on the environment. Applicable modeling scales range from streams and rivers to dynamically driven lakes, bays and coastal estuaries.

Additional duties will include modeling to predict the impacts of floods following extreme rainfall events or dam break scenarios. Job responsibilities also include possible collaboration with ATG atmospheric scientists on a range of modeling applications and analyses.

The applicant should possess a graduate degree in hydrology or a science or engineering discipline relevant to hydrodynamic modeling and 3-14 years pertinent experience.

Familiarity with the Environmental Protection Agency's WASP and BASINS modeling systems and the U. S. Army Corps of Engineers HEC-RAS model is highly desirable. The successful candidate must possess excellent written and oral communication skills, willing to present their work at professional conferences and government forums, and comfortable advocating for surface water modeling program capabilities within SRNL National Security Directorate work groups or other potential U. S. government sponsors.

The SRNL is located on the U. S. Department of Energy's Savannah River Site in South Carolina near Augusta, GA, and is operated for DOE by Savannah River Nuclear Solutions, LLC. For more information contact: Mr. Chuck Hunter, 803-725-2953, chuck.hunter@srnl.doe.gov. Interested candidates should apply through http://srnl.doe.gov > Careers > SRNL Jobs. Search for job number 4658BR. U.S. citizenship is required.

Science and Engineering postdoctoral Enrichment and Development program (SEED) Postdoctoral Scholar. POSITION DETAILS: The Applied Physics Laboratory at the University of Washington (APL-UW) is seeking Postdoctoral Scholar with research interests in Oceanography, Ocean Engineering, Underwater Acoustics, Marine Robotics, Marine Energy, Polar Science, Medical Ultrasound, Signal Processing, and Autonomy. These are full-time (100% FTE) appointments, with expected terms of two years subject to satisfactory performance and availability of funding.

Positions are not project-specific; each applicant is expected to define his/her research goals within the broad program areas of the participating APL departments: Air-Sea Interaction & Remote Sensing, Acoustics Department, the Center for Industrial and Medical Ultrasound, Electronics and Photonics Systems, Environmental Information Systems, Ocean Engineering, Ocean Physics, and the Polar Science Center (PSC). Applicants are strongly encouraged to contact potential APL mentors before submitting an application.

Promotional and further developmental opportunities following the completion of the post-doc appointment are possible subject to availability of funds and the demonstration of an interest in developing independent research initiatives during the course of the post-doc appointment. Opportunities to collaborate with scientists across the UW campus provide access to a broad range of expertise both during the post-doctoral research and as a permanent member of the staff.

APL-UW serves society by contributing new knowledge and technology to the national defense enterprise, industry, public policy makers, and academia. The Laboratory's broad and deep experience in undersea science and technology is a significant reason why APL-UW is one of only five Department of Defense-designated University Affiliated Research Centers (UARCs) having long-term, large-scale, formal connections to the U.S. Navy.

The University of Washington is located in the greater Seattle metropolitan area, with a dynamic, multicultural community of 3.7 million people and a range of ecosystems from mountains to ocean. The University serves a diverse population of 80,000 students, faculty and staff, including 25% first-generation college students, over 25% Pell Grant students, and faculty from over 70 countries. The University promotes diversity and inclusivity among our students, faculty, and staff and the public; we seek applicants who are committed to these principles. Thus, we are strongly seeking applicants whose research, teaching, and/or service have not only prepared them to fulfill our commitment to inclusion, but have also given them the confidence to fully engage audiences in higher education from a wide spectrum of backgrounds.

The position offers a yearly salary of $63,500. Additional funding support to include a research allowance of $4,000, and a relocation allowance of $2,000. This position will be eligible for certain University benefits. A comprehensive description of UW academic personnel benefits is available at http://hr.uw.edu/benefits/.

Requirements:

- Excellent verbal and written skills.
- Strong research skills.
- Ability to work independently.
- Effective problem solving/critical thinking skills.
- Strong technical communication and collaboration skills.

Educational requirement: PhD in related scientific or engineering field with no more than 36 months inclusive of all postdoctoral experiences

Limitations on Appointment: Appointment not to exceed 5 years, including postdoctoral experience(s) at other institutions. Postdoctoral Scholars are engaged in full-time mentored advanced training to enhance professional skills and research independence, and perform primarily research and scholarship under the direction and supervision of University faculty mentors.

CONDITION OF EMPLOYMENT:

Postdoctoral scholars are represented by UAW 4121 and are subject to the collective bargaining agreement, unless agreed exclusion criteria apply. For more information, please visit the University of Washington Labor Relations website (https://hr.uw.edu/labor/2019/06/03/agreement-reached-with-uaw-postdoctoral-scholars-on-2019-2021-contract).

Application Instructions

To request disability accommodation in the application process, please contact the UW's Disability Services Office at 206-543-6450, or 206-543-6452 (TTY), or dso@uw.edu.

The application deadline is January 6, 2020, and finalists will be contacted in February 2020. Travel expenses will be covered to allow finalists to present their recent work in an APL seminar in Seattle, WA.

Job offers be will be made in April 2020 with start dates negotiable between May 2020 and December 2020.

Applicants are asked to submit electronically:

1. A curriculum vitae,
2. A publication list,
3. A brief research proposal (no more than 5 pages, double-spaced, excluding bibliography and figures) describing research to be pursued during a two-year tenure at the University of Washington, and
4. The names of four individuals who can provide a letter of reference.

In addition, a letter of support from a potential mentor in one of the participating departments is strongly encouraged. Further information on current research at APL, by department and principal investigator, can be found at: http://www.apl.washington.edu/departments/departments.php

Questions can be submitted preferably via email to:

Andy Jessup
jessup@uw.edu
Applied Physics Laboratory – University of Washington
1013 NE 40th Street
Box 355640
Seattle, WA 98105-6698

Tenure Track Assistant Professor in Remote Sensing/Geospatial Technology. The Geological Sciences Department at California State Polytechnic University, Pomona, invites applications for a tenure-track, ASSISTANT PROFESSOR position, beginning in the 2020-2021 academic year. We invite applications from geoscientists whose research incorporates data from ground-based remote sensing or observations from unmanned aerial vehicles or satellites. The position is open to a broad range of research specializations, such as natural hazards, active tectonics, environmental geoscience, and/or climate change. A Ph.D. in geology, geophysics, environmental geoscience or a directly related science or engineering discipline is required. The successful candidate will have the potential for excellence in teaching, and for developing an externally-funded research program that will involve undergraduate and Master's students. Teaching responsibilities will include a mix of geoscience courses at the lower division, upper division, and graduate levels, and incorporate classes in Geographic Information Systems, Remote Sensing or other specialty courses in the candidate's area of expertise. Demonstrated experience with data collection and analysis using modern instrumentation is expected. Preferred qualifications include demonstrated success with external funding, established ties to research institutions, industry or government agencies and interest in developing intradepartmental and cross-campus collaborations. At Cal Poly Pomona we cultivate success through a diverse culture of experiential learning, discovery, and innovation. Cal Poly Pomona is committed to being the model for an inclusive polytechnic university. The position is open until filled. First consideration will be given to completed applications received no later than December 30, 2019. Apply at https://apply.interfolio.com/66998

Natural Hazards

Assistant Professor – Geohazards. The Department of Earth and Environmental Sciences at the University of Texas Arlington invites applications for a tenure-track faculty position in broadly construed areas related to geohazards or environmental health at the level of Assistant Professor. Faculty candidates for higher ranks with exceptional track records will also be considered. We seek a broadly-trained geoscientist or environmental scientist who complements the interdisciplinary nature of our earth and environmental science program. While candidates from all subdisciplines of earth and environmental sciences are encouraged to apply, we are particularly interested in candidates with expertise in one of the following areas: geohazards, processes leading to earthquakes, rock strength change, landform response to disturbances, climate change and its impact, data analytics, dynamical or statistical modeling, the exposome, biomarkers, and metabolics. Opportunities for collaboration exist with departmental research groups in geochemistry, petrology, sedimentary geology, environmental health and toxicology, climate change and paleoclimatology, paleontology, hydrogeology, and other research groups of data science, analytical chemistry, ecology, and genomics in the College of Science, the College of Architecture, Planning, and Public Affairs, and the College of Engineering. Our analytical strengths include the on-campus Shimadzu Institute for Research Technologies (http://www.uta.edu/sirt/), particularly the Shimadzu Center for Environmental, Forensics, and Material Science, an ultraclean laboratory, and a gas isotope ratio mass spectrometer housed within the Earth and Environmental Science and the novel Science & Engineering Innovation & Research buildings.

Applicants should have a doctoral degree in earth and environmental sciences or a related field. Successful candidates are expected to demonstrate a commitment to diversity and equity in education through their scholarship, teaching, and/or service.

To apply online at https://uta.peopleadmin.com/postings/10400 . A complete application includes: 1) curriculum vitae, 2) summary of current and proposed research (max. two pages), 3) statement of teaching interests (max. one page), and 4) names and email addresses of three references.

Review of applications will begin immediately and continue until the position is filled. For full consideration, applications should be submitted by November 16th, 2019.

Question regarding this position may be directed via email to Dr. Majie Fan, Search Committee Chair (email: mfan@uta.edu) or the Department of Earth and Environmental Sciences administration (email: lpanther@uta.edu).

UTA is an Equal Opportunity/Affirmative Action institution. Minorities, women, veterans and persons with disabilities are encouraged to apply. Additionally, the University prohibits discrimination in employment on the basis of sexual orientation. A criminal background check will be conducted on finalists. The UTA is a tobacco free campus.

Ocean Sciences

Professor of Oceanography, University of Rhode Island. The Graduate School of Oceanography (GSO), University of Rhode Island (http://www.gso.uri.edu) invites applications for the position of Professor of Oceanography whose primary focus will be exploration that integrates ship-based field programs, innovative technology development (with emphasis on autonomous systems), and broad-based educational outreach activities.

Located on the water's edge at URI's Narragansett Bay Campus, GSO is the state's center for marine studies, research and outreach. The successful applicant will assume a leadership role as co-P.I. in the recently funded, 5 year NOAA Ocean Exploration Cooperative Institute led by GSO with its institutional partners, the University of New Hampshire, the Woods Hole Oceanographic Institution and the University of Southern Mississippi. The applicant is expected to develop externally funded research programs, advise graduate students, and teach undergraduate and graduate courses.

The search will remain open until the position is filled. First consideration will be given to applications received by January 11, 2020. Second consideration may be given to applications received by February 29, 2020. Applications received subsequent to the second consideration date (February 29, 2020) may not be given full consideration.

Visit https://jobs.uri.edu and search posting number (F00174) for the full position description, required and preferred qualifications, and application instructions.

The University of Rhode Island is an AA/EEOD employer. Women, persons of color, protected veterans, individuals with disabilities, and members of other protected groups are encouraged to apply.

Tenure Track Scientist, Applied Ocean Physics & Engineering Department. The Applied Ocean Physics & Engineering Department at the Woods Hole Oceanographic Institution invites candidates to apply for tenure-track scientific-staff positions to complement and expand existing programs in coastal oceanography & fluid dynamics; underwater acoustics, acoustical oceanography & signal processing; field robotics & machine learning with applications to marine environments. For more information/to apply online, please visit https://careers.whoi.edu/opportunities/view-all-openings/science-research/ postings 19-10-12, 19-10-13, 19-10-14.

Tenure Track Scientist, Biology Department. The Biology Department at the Woods Hole Oceanographic Institution (WHOI) invites applications for a full-time tenure-track position at the Assistant Scientist level on our Scientific Staff (www.whoi.edu/biology). We seek outstanding candidates to complement our existing interdisciplinary strengths in biology, biological oceanography, and marine ecology. We are particularly interested in applicants who conduct research in behavioral ecology of marine top predators; areas of focus may include (but are by no means limited to) social, ecological, evolutionary and anthropogenic determinants of behavior. Please visit http://careers.whoi.edu and respond to Job Reference 19-10-06. Applicants should include, as a single PDF document: a cover letter, curriculum vitae, three-page research statement, names and contact information of four references, and copies of up to three relevant publications or preprints.

Tenure Track Scientist, Marine Chemistry & Geochemistry Department. The Marine Chemistry & Geochemistry Department at the Woods Hole Oceanographic Institution (WHOI) – www.whoi.edu–invites exceptional candidates to apply to one or more of our tenure track positions on our scientific staff. The successful candidate(s) will conduct research in any area of marine chemistry and geochemistry that complements existing programs on the chemistry of the ocean and its interactions with the Earth as a whole. Core departmental strengths include: biogeochemistry and organic geochemistry; microbial ecology and molecular biology; carbon, nutrient, and trace element cycling; environmental change including climate change, air sea exchange; photochemistry; coastal, estuarine, wetland and river geochemistry & biogeochemistry; sediment geochemistry; fluid-rock interactions; igneous geochemistry; noble gas geochemistry; and isotope systematics, including radiochemistry. MC&G scientific staff conducts research throughout the world's open-ocean, deep-sea, coastal and inland environments, develops sensors for in-situ measurements, analyzes samples using state-of-the-art analytical techniques, carries out laboratory-based experimental studies, and applies computer models and remote sensing techniques. For more information about this job and to apply online, please visit http://careers.whoi.edu, navigate to "Current Opportunities" and respond to Job Reference 1-10-11. Review of applications will begin on 12/16/2019.

Tenure Track Scientist. The Physical Oceanography Department at the Woods Hole Oceanographic Institution (http://www.whoi.edu/main/PO) invites applications for a tenure track position on our scientific staff. The successful candidate will join a collaborative group of scientists who address a wide range of fundamental problems in ocean and climate physics, as well as interdisciplinary research questions. A world-class technical staff supports the use of a broad mix of traditional and innovative instruments and observational techniques to make measurements on all scales from microstructure up to global, and in all ocean domains including open-ocean and coastal regions. We welcome qualified applicants working in physical oceanography or a related field regardless of approach (observational, modeling, theory), and encourage those interested in the interplay between ocean dynamics and other components of the Earth system. We expect to hire at the Assistant Scientist level, but exceptional candidates at more senior levels may be considered.

Applicants should have a doctoral degree, postdoctoral experience, and a record of peer-reviewed publications. Scientific staff members are expected to develop independent, externally funded, and internationally recognized research programs. They also have the option of advising graduate students and teaching courses through the MIT/WHOI Joint Program in Oceanography and Oceanographic Engineering (http://www.whoi.edu/jointprogram/).

Opportunities for interdisciplinary research exist through collaborations with colleagues in the other science departments, centers, and labs at WHOI (www.whoi.edu/main/departments-centers-labs) as well as with researchers in the broader Woods Hole scientific community. Members of WHOI's Scientific Staff are expected to provide for their salaries from grants and contracts. The Institution provides salary support when no other funding is available, as well as numerous internal funding opportunities for developing innovative research projects. Candidates hired at the junior level will receive an initial appointment for four years with guaranteed salary.

WHOI is the largest private, non-profit oceanographic institution in the world, with staff and students numbering approximately 1,000. Its mission is to advance our understanding of the ocean and its interaction with the Earth system, and to communicate this understanding for the benefit of society. The Institution is located in Woods Hole, Massachusetts, a world-renowned center of excellence in marine, biomedical, and environmental science.

WHOI is committed to supporting a diverse and inclusive working environment and is proud to be an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, gender, gender identity or expression, sexual orientation, national origin, genetics, disability, age, or veteran status. WHOI believes diversity, equity, and inclusion are essential components that support our academic excellence. We strive for a diverse and inclusive workforce, and encourage women, minorities, veterans and those with disabilities to apply.

WHOI offers a comprehensive benefit package that includes medical and dental plans, child care subsidy, an employer contribution retirement plan, vacation time, flexible scheduling, and family illness days. WHOI also provides dual career services for assisting your spouse or partner should they be impacted by your career decision. We have a dedicated team who will work with applicants to identify and explore available options within WHOI or the broader community.

HOW TO APPLY:

Please visit careers.whoi.edu and respond to Job Reference 19-10-05. Applicants should include, as a single PDF document: a cover letter, curriculum vitae, three-page research statement, names and contact information of four references, and copies of up to three relevant publications or preprints. Review of applications will begin on December 16 and will continue until the positions are filled.

WHOI is a member of the Higher Education Recruitment Consortium (HERC). Please visit HERC for more information.

WHOI is an Affirmative Action/Equal Opportunity Employer. Applicants that require accommodation in the job application process are encouraged to contact the EEO Officer at eeo@whoi.edu or at 508-289-2705 for assistance

Volcanology, Geochemistry, and Petrology

Assistant Professor, Earth Materials. The School of the Environment at Washington State University invites applications for an Assistant Professor in Earth Materials, to begin August 2020, with an emphasis in petrology, mineralogy, volcanology, magmatic processes, or tectonic processes. The candidate will take a leadership role in developing and funding research initiatives that take advantage of WSU's Peter Hooper GeoAnalytical Laboratory and the Radiogenic Isotope and Geochronology Laboratory, which maintain state-of -the art capabilities in whole rock and micro-scale major and trace element analysis, geochronology, and radiogenic and stable isotope geochemistry. Lab facilities include current generation electron microprobe, X-ray fluorescence, inductively-coupled plasma mass spectrometer, and laser ablation facilities (https://environment.wsu.edu/facilities/geoanalytical-lab/).

The successful candidate will: (i) develop an externally funded research program; (ii) publish research in top quality journals; (iii) teach undergraduate and graduate courses in Earth Materials; (iv) mentor graduate students; (v) take a leadership role in the GeoAnalytical Laboratory; (vi) work with faculty and mentor students from a wide range of backgrounds; and (vii) serve university and professional organizations. To learn more and apply, visit: https://www.wsujobs.com/postings/48041

WSU is an EO/AA Educator and Employer.

Assistant Professor in Earth and Planetary Sciences. The Department of Earth and Planetary Sciences (EPS) at Rutgers University-New Brunswick invites applications for a tenure-track Assistant Professor with an expected start date of Sept. 1, 2020. Applicants must have a Ph.D. at the time of appointment. Entry at a higher rank may be considered for extraordinary candidates with appropriate experience. We seek outstanding candidates in the fields of mineralogy, petrology, geochemistry, and paleobiology whose work relates to the co-evolution of physical, chemical, and biological systems of the Earth and/or other rocky planetary bodies, including: 1) large-scale planetary processes and long-term evolution of minerals, geochemical reservoirs, atmospheres and oceans, and/or planetary habitability, particularly of the early Earth; 2) mechanisms and controls on planetary surface processes, and the history of their operation; and 3) long-term molecular, evolutionary, and ecological relationships between biodiversity and planetary change recorded in sedimentary records. We encourage candidates whose interdisciplinary work crosses traditional departmental boundaries. Faculty in EPS are expected to be enthusiastic instructors, typically teaching one course per semester either in the undergraduate or graduate program.

Applicants should submit a cover letter; a 2-3 page statement of research accomplishments and vision; a 1-2 page statement of teaching and mentoring history with proposals for enhancing diversity within the department and the university; a curriculum vitae; plus names and contact information for at least three referees. Submit all materials to [https://jobs.rutgers.edu/postings/102136]. Review of applications begins November 30, 2019 and will continue until the position is filled.

Address questions to Kenneth Miller, search committee chair, at kgm@eps.rutgers.edu

G'day, Mate!

Greetings from Alice Springs, Northern Territory, Australia, where we are studying the hydrologic effects of human and climatic stresses on water-limited areas and how differences in the availability of resources can explain the functionality of the vegetation. Arid and semiarid environments account for approximately 30% of the Earth's continental surface and are especially sensitive to degradation or loss of their ecosystem functionality.

In these ecosystems, vegetation patterns (e.g., banded vegetation) have been found to be the adaptive response of the system to resource redistribution (runoff and sediments) and limitation (soil moisture and nutrients). The patterns consist of alternating densely vegetated bands (groves) and bare areas (intergroves) and can be found in large regions of Africa, Asia, Australia, and North America.

Monitoring the properties that regulate these ecosystems is critical to understanding their dynamic behavior and maintaining their functionality. We are conducting soil carbon, nutrient, and soil moisture sampling and unmanned aerial vehicle flights for remotely sensed lidar capture for the banded vegetation. This research is being carried out thanks to the Australian Research Council and the University of Newcastle.

—**Patricia Saco, Dominik Jaskierniak,** and **Juan Quijano,** University of Newcastle, Australia, Callaghan, N. S. W.

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