VOL. 100 • NO. 3 • MAR 2019

EOS
Earth & Space Science News

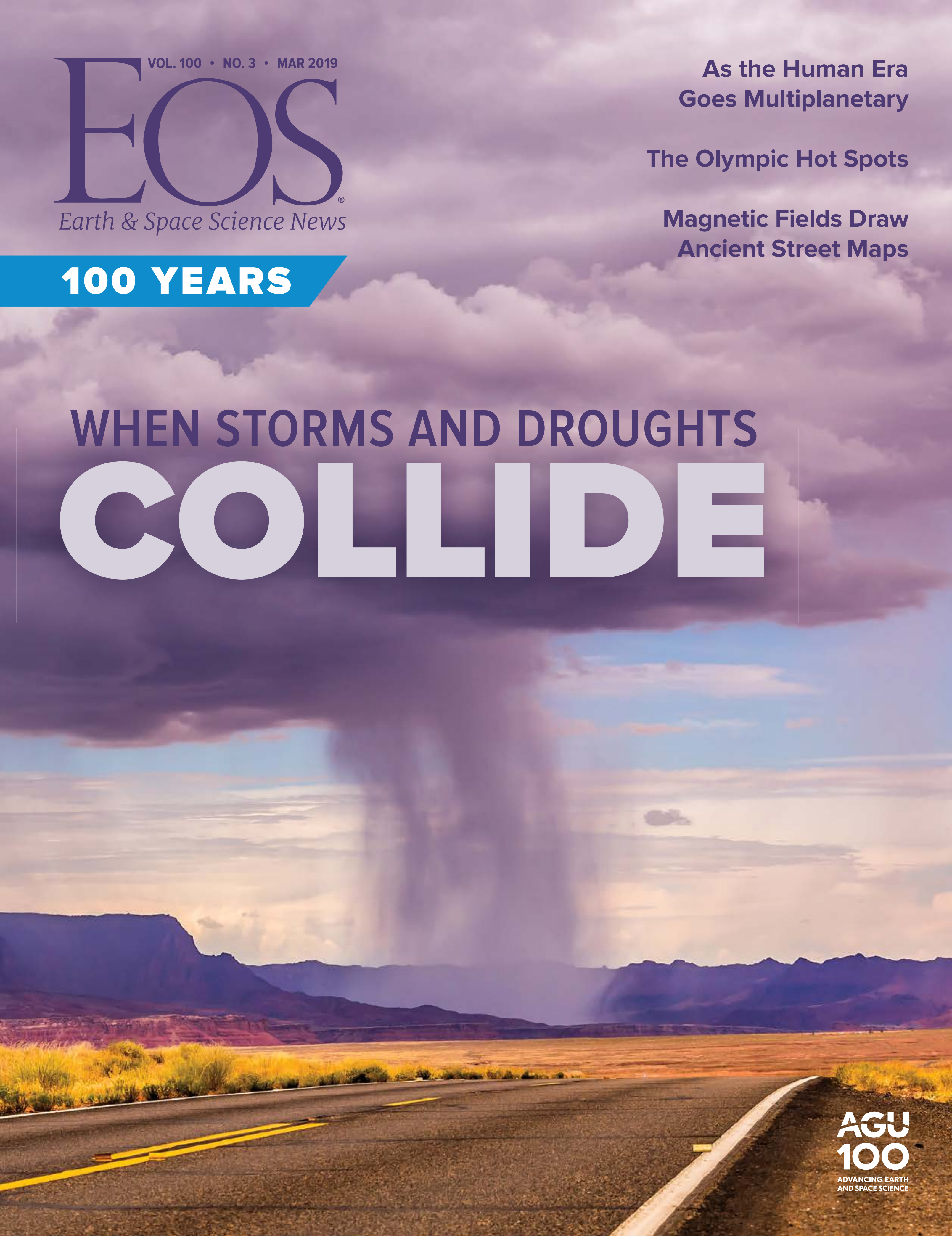
100 YEARS

As the Human Era Goes Multiplanetary

The Olympic Hot Spots

Magnetic Fields Draw Ancient Street Maps

WHEN STORMS AND DROUGHTS COLLIDE



AGU 100
ADVANCING EARTH AND SPACE SCIENCE

Everything Is Connected

"Water problems are few but basic," wrote Raymond L. Nace, a research hydrologist at the U.S. Geological Survey, in 1969. Scientists in his field had come together 5 years earlier to launch the International Hydrological Decade (IHD), a program by the United Nations Educational, Scientific and Cultural Organization (UNESCO). Nace, who chaired the program committee, was ready to offer an update on their progress.

Much of that progress was a massive push for awareness, by focusing research on areas of the world that best exemplified those few but basic problems Nace identified: "distribution in space (too much or too little); distribution in time (too much in some seasons or years and not enough in others); chemical quality [from naturally occurring minerals]; and pollution." Groups were formed in nearly 100 countries. They looked at issues affecting their own neighborhoods and, more importantly, began the first major international collaboration to learn more about how those processes pushed and pulled each other around the globe. (Read more about the IHD during March on Eos.org.)

As AGU looks back this year in celebration of our Centennial, one of our prouder moments is the significant role we played in guiding U.S. involvement in the IHD. Our organization brought the idea back from discussions during the 1960 Helsinki meeting of the International Union of Geology and Geodesy, forming a committee that led to the 1962 formation of the Conference of American Hydrologists. That group published a report "that represented a major contribution to the visibility of scientific hydrology," as we wrote here in the pages of *Eos* in May 1990.

The groundwork laid during that era brought us to today, when leaders in most nations understand that the need for sound water policy is paramount, not simply because they've suffered floods or droughts but because scientists have been able to give clarity regarding the causes of these hydrological extremes and how they're connected both to far-away systems and to human actions very much under our control.

Of course, the complexity of these processes can still be staggering. Our cover story this issue (p. 24) explores what happens when these extremes collide. Scientists and governments have given much attention in the past few decades to discrete natural hazards and the toll they take on a population. Floods alone, between 1980 and 2013, have taken more than 200,000 lives and caused $1 trillion in damage around the globe. Now, a group of scientists argue, we need to turn our attention to compound events—when two or more hazardous events or climate variables collide—which are largely overlooked today in disaster risk analysis.

Meanwhile, even when scientists have been able to create solid models, climate change continues to shake up everything. The rapid thawing of permafrost has far-reaching effects on hydrological and geomorphological processes. On p. 30, a group of scientists explains how they developed a new Permafrost Modeling Toolbox to help research these questions. Designed for education, industry research, and the academic community, the three models in the toolbox allow users to calculate permafrost in specific regions, create maps of future permafrost, and compare models of different complexities.

Long before the International Hydrological Decade, AGU understood the great need to study these globe-spanning processes. In 1930, the Section of Hydrology was officially established, drawn out from the special committees who were asking increasingly important questions about the world. As AGU positions itself for the next century, we are eager to support and listen to the scientists who continue to reveal our planet's intricate systems.

Heather Goss, Editor in Chief

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

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

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A sudden downpour sweeps across a desert valley in Arizona.
Credit: Amir AghaKouchak

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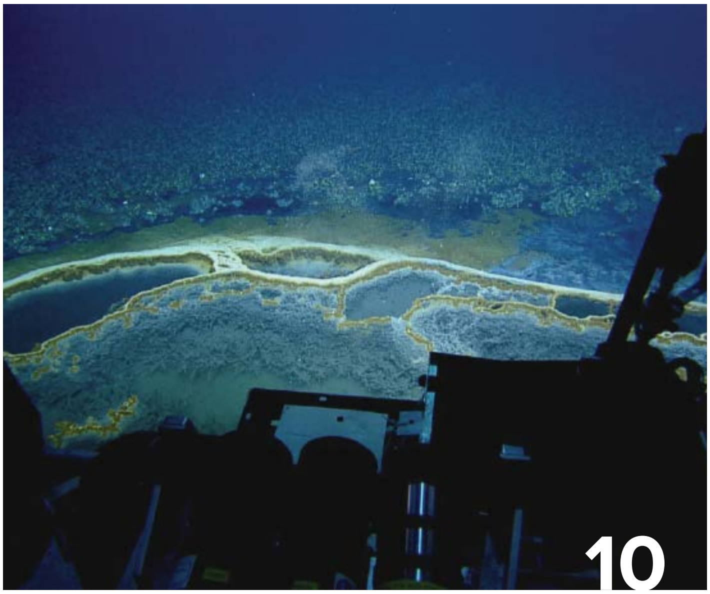


Columns

EOS CENTENNIAL COLLECTION

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Tracing the Path of Carbon in North America

The same day that the National Climate Assessment was released last November, a different report was quietly released by its side: the *Second State of the Carbon Cycle Report.* The report tracks carbon as it moves through ecosystems, from forests to cities to coastal waters and more, and it serves as the most comprehensive evaluation of carbon cycle science in North America for the past decade.

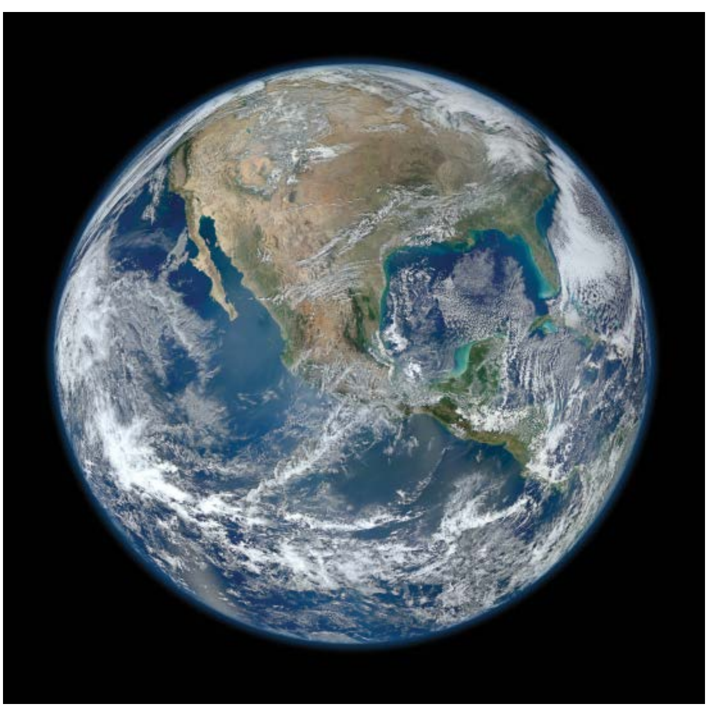
"Carbon is the basis of life on Earth," Gyami Shrestha, director of the U.S. Carbon Cycle Science Program and an editor of the report, told *Eos.* "When it binds with oxygen, hydrogen, and nutrients, it creates the basis of all living beings on Earth, and it's essential for human activities."

"Carbon is very critical in regulating climate," Shrestha said. "It's important to know how we are impacting Earth, and how the carbon cycle is impacting Earth."

The report, the second iteration published by the intergovernmental U.S. Global Change Research Program, includes research since 2007 across the United States, Mexico, and Canada. More than 200 scientists from research institutions, national laboratories, government agencies, universities, and the private sector served as authors, pulling from research spanning more than 3,000 publications. The result is a comprehensive assessment of carbon cycling in land, air, and water in North America.

Here are some of the main findings from the more than 900-page report:

- Since the Industrial Revolution, carbon dioxide (CO_2) has increased in our atmosphere by 40%. Methane concentrations have skyrocketed in the same time period, increasing by 160% in our atmosphere.
- North America reduced its share of global fossil fuel emissions from 24% to 17% in the time span between 2004 and 2013. Industries switching energy sources to natural gas instead of coal and improvements in vehicle efficiency largely explain the drop, as does the increase in emissions from other continents.
- Forests, grasslands, and other land ecosystems have been sucking up carbon to the tune of 600–700 teragrams per year in North America (for scale, that's about a third of the continent's annual fossil fuel emissions).
- The data on how much carbon our coastal waters take in and lock away still have large uncertainties. But researchers did highlight how much gets absorbed by certain ecosystems, such as tidal wetlands and estuaries, which suck up 17 teragrams of carbon per year and bury the majority in their sediments.
- Although methane continues to build up in our skies globally, North America is not increasing its emission rates, even though it has been amping up natural gas use.
- Cutting emissions of greenhouse gases (GHGs) in North America by 80% of 2005 levels will cost \$1–\$4 trillion from 2015 to 2050. The number may pale in comparison with how much damage caused by climate change could cost in the future. By 2050, for instance, the bill for climate change damages may amount to \$170–\$206 billion in that year alone.
- Urban areas in North America expel the most carbon of any location, yet those sources are among the hardest to track.
- Frozen soil in the Arctic is melting and could release 5%–15% of its carbon stores by the end of this century.
- The waters off Oahu, the Aleutian Islands, and the Gulf of Maine are acidifying, and the low pH is already altering ecosystems.



From forests to soils to coastal waters to the atmosphere, carbon is literally all around us. A new report maps its path around North America and explores the fate of the carbon as fossil fuels continue to burn. Credit: NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring

The report details some paths forward: "Recently, many U.S. states, led by their governors, have made state-level commitments to reduce GHG emissions," the authors wrote in the report's executive summary. In addition, scientists should work toward resolving open questions, including how CO_2 feedbacks could tweak terrestrial ecosystems and precisely how humans are shaking up the carbon cycle.

Still, the authors behind the fourth edition of the National Climate Assessment (NCA4) wrote in *Eos* (see bit.ly/Eos-NCA4) that current global and regional efforts to mitigate the causes of climate change are not drastic enough to avoid "substantial damages to the U.S. economy, environment, and human health and well-being over the coming decades."

"Instead, more immediate and substantial global greenhouse gas emissions reductions and more regional adaptation efforts would be needed to avoid the most severe consequences in the long term," the NCA4 authors wrote.

Shrestha agrees, reminding us that the United States contributes the majority of emissions for North America.

"The U.S. has been able to decrease its emissions," Shrestha said of the past decade. "But it's not been enough."

By **Jenessa Duncombe** (@jrdscience), News Writing and Production Intern

Next Olympic Marathon Course Has Dangerous "Hot Spots" for Spectators

Olympic spectators (at the London 2012 Games, above) often wait for hours in the sun to cheer marathon competitors. Credit: iStock.com/photocritical

Tokyo isn't the ideal place to visit in summer, especially if you're standing around outside for several hours: Temperatures regularly hover near 30°C (86°F), and it's humid. But in August 2020, thousands of spectators are expected to crowd along a 42.2-kilometer course to watch the marathon event as Tokyo hosts the Summer Olympics. Now, for the first time, researchers have studied weather conditions along this course to pinpoint spots where spectators' health may be jeopardized by high levels of heat. On the basis of their findings, the scientists are talking with Olympic officials about ways to make spectators more comfortable, for example, by placing containers of shade-providing vegetation along the course or rerouting a leg of the race to a more tree-lined street.

A Bicycle Built for Instruments

Jennifer Vanos, an atmospheric scientist at Arizona State University's School of Sustainability in Tempe, and her colleagues collected data—including for air temperature, solar radiation levels, humidity, and wind speed—in August 2016 along the Tokyo marathon course using a suite of meteorological instruments mounted on a bicycle. The scientists also calculated the "sky view factor"—the proportion of the sky visible at any one place—from Google Street View images to estimate the impact of structures such as buildings reradiating heat. Vanos and her collaborators then used these meteorological data in combination with estimates of human physiology to calculate a human heat load, that is, the net amount of heat that a person gains or loses. They found that hypothetical spectators along some parts of the marathon course would take in much more heat from the environment than they could lose by, for instance, sweating.

Forecasting potential heat stress dangers at specific locations could save innumerable lives.

Three Spots to Avoid

The scientists pinpointed three spots, all along the second half of the course, where spectators would be exposed to a high heat load. One of these locations, the square in front of the Imperial Palace, is an open area with limited trees and no buildings nearby to provide shade. It's also a beautiful, historic area, Vanos acknowledges, which means that Olympic officials are unlikely to reroute the course to avoid it. But it would be a great spot to position extra resources like fans, water stations, and emergency personnel, the researchers suggest. Getting air moving is important for helping people cool off, said Vanos. "One of the biggest factors when it comes to crowding is that there is just no wind movement."

The other two areas, both with limited shade, would benefit from the installation of shade sails, trellises of vegetation, and potted trees that could then be planted elsewhere in Tokyo after the games, Vanos and her colleagues suggest. These results were published last December in *Science of the Total Environment* (bit.ly/marathon-course) and presented in January at the American Meteorological Society's Annual Meeting in Phoenix, Ariz.

These results are important because heat is much more than just an inconvenience: It can kill people, said Kim Knowlton, a climate-health scientist at the Natural Resources Defense Council in New York, N.Y., not involved in the research. "Forecasting potential heat stress dangers at specific locations gives planners a way to target their heat preparedness efforts, which could save innumerable lives."

By **Katherine Kornei** (hobbies4kk@gmail.com; @katherinekornei), Freelance Science Journalist

House Science Committee Comes Out of the Wilderness

Rep. Eddie Bernice Johnson, a Democrat from Texas who became the chairperson of the House of Representatives' Committee on Science, Space, and Technology in January, is proving that elections make a difference.

Johnson has planned a full and active agenda for the committee to address the challenge of climate change and ensure U.S. global leadership in science, technology, engineering, and mathematics (STEM) areas. Also on the agenda is to "restore the credibility" of the committee "as a place where science is respected and recognized as a crucial input to good policy making," Johnson said in a statement after the Democrats won back the House in last November's midterm elections.

The committee promises to have a very different focus than it did under its former chair, retired Rep. Lamar Smith (R-Texas). Smith has called climate scientists "alarmists," and his hometown newspaper, the *San Antonio Express-News,* has criticized Smith for the "abuse of his position" as committee chair.

Johnson spoke with *Eos* about the agenda of the science committee, which she calls a "committee of the future."

Out of the Wilderness

Johnson said that it was difficult to be in the minority on the committee when Smith was chairman. "It was not easy to be in the wilderness for so many years, because I kept thinking every day how we"—the committee—"were misstepping and essentially wasting time and trying to interfere with the various agencies that were looking and planning for the future rather than supporting them. That part of it we will end," she said.

Johnson intends to address the challenges of climate change head on. "We're talking about setting goals for the future existence of human beings on this planet," Johnson said. "It is a global issue. And, as our history has planted us as leaders on the planet, we are expected to be leaders. And here we are denying that such a thing has even occurred when we get information every day about the melting in the Arctic, the bodies of water getting fuller. The planet is hotter than it's ever been. All of these effects affect human existence and how we have to deal with that. We've got to get that information out. We've got to start taking those small steps that make a dent after a period of time to change some of that."

For the past 6 years, the attitude "was more protecting the fossil fuel industry [and] denying that some change needs to come, rather than ushering in some direction of change," Johnson said. She already has discussed climate change with ExxonMobil's CEO, who, according to Johnson, expressed his concern about the United States withdrawing from the Paris climate accord. "It is not either us or them," said Johnson, who represents parts of Dallas County and the surrounding area. ExxonMobil's world headquarters are near her district and used to be within the district. "It is working together with industries because new technology will bring about new good, paying jobs."

"We want to saturate the committee with that knowledge [about climate change] to make it look stupid to be in denial. That's our number one goal."

Climate Change Hearings

Johnson said committee hearings about climate change could focus on many different angles. "We've got to hear from the researchers, the scientists, and we've got to do lots of that, because we haven't had any of it in the past 6 years," Johnson said. "We want to saturate the committee with that knowledge [about climate change] to make it look stupid to be in denial. That's our number one goal."

Johnson also noted that her committee is working with other committees that have similar jurisdictions to "see if we can't do something more coordinated." That includes the new House Select Committee on the Climate Crisis, which House Speaker Nancy Pelosi announced last December.

Johnson said that the select committee could make recommendations but that unlike the standing committees, it will not have legislative or subpoena authority. "We could do the same thing with standing committees, but this was something I think that was committed to some of the new people [in Congress]. We will work with them to see whether or not we've got two or three tracks running or whether we can collaborate together. I don't anticipate that there will be friction" between the select committee and the standing committees, she said.

Common Sense of What Is Possible

Select committee chair Rep. Kathy Castor (D-Fla.) was quoted in January in *The Hill* as saying that the committee will be "clearly in the spirit of the Green New Deal." Rep. Alexandria Ocasio-Cortez (D-N.Y.), an early supporter of the Green New Deal, an initiative calling for bold action to address climate change, has tweeted that she applauds the select committee but that it is too weak without subpoena power.

Johnson told *Eos* that "it's difficult to tell" whether the Green New Deal is too ambitious, too naive, or right on track. "I just know this: Whatever we are going to do is not going to happen overnight. Whatever we are going to do, we have got to make sure that every step is a sound step based on sound research and based on what we can afford to do at the time. So it's good to have the ambitiousness. It's good to have many of the ideas, but common sense has to set in at some point, too, of what's possible," she said.

Supporting Science and Science Agencies

With the science committee having jurisdiction over much of the nation's nondefense federal research and development portfolio, Johnson highlighted her support for federal science agencies, many of which, including the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA), came under attack by the committee's previous chair, Rep. Smith. Johnson said that several other concerns include the direction of the Environmental Protection Agency and environmental rollbacks there, questions about the Trump administration's proposal to end direct funding for the International Space Station by 2025, and getting detailed information about the administration's proposed Space Force.

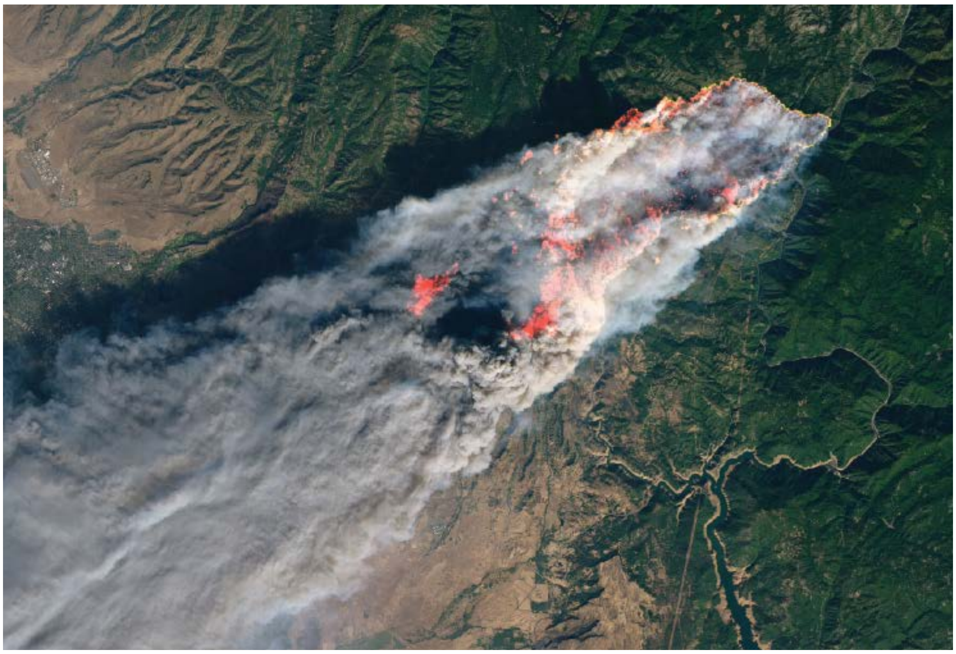
A Way Forward

Johnson is optimistic about making progress. "We are not going to do miracles overnight, but we can chart a way to get there step by step," she said.

What would Johnson want to tell President Trump about climate change? "I would try to convince him how important it is to face the truth," the chairperson told *Eos*.

By **Randy Showstack** (@RandyShowstack), Staff Writer

Invisible Wildfire Smoke Has Visible Health Impacts



This 8 November 2018 Landsat 8 photo shows smoke from the Camp Fire near Paradise, Calif. Areas of active burning, detected using shortwave infrared sensors, are highlighted in red. Credit: NASA Earth Observatory

Smoke from California wildfires in 2015 may have led to an increase in asthma-related doctor visits in Colorado, recent research shows. This finding could influence how communities are warned about smoke hazards.

Severe wildfires, like the recent Camp Fire in Paradise, Calif., have been increasing across the West, devastating nearby communities. Data presented in December at AGU's Fall Meeting 2018 in Washington, D.C., highlight the impact that even distant wildfire smoke could have on our respiratory health.

"Wildfire smoke is different than what you breathe out on the street," said Katelyn O'Dell, a graduate student from Colorado State University in Fort Collins who presented the findings. Ambient air pollution from cars and factories has already been linked to a number of health problems, including acute respiratory infections, heart disease, and lung cancer. Some of this pollution is soot that you can see, but air particles that are less than 2.5 micrometers in diameter—think 30 times smaller than the width of a human hair—are especially harmful to our health because they can penetrate deep into our lungs and cross into our bloodstream. Particles from smoke tend to fall into this category.

Carbon dioxide, water vapor, carbon monoxide, and thousands of other compounds are blended together in smoke, but it remains unclear what the health consequences are. Thus, understanding how the wildfire season affects the respiratory system would be valuable.

"Wildfires come through and increase [exposure] dramatically for a couple days," O'Dell said. "So you can imagine being exposed to a lot of it just for a few days might have a different health impact than being exposed to a mild amount of particles for your whole life."

Scrutinizing Smoke

O'Dell and her colleagues looked at three different fire seasons: Washington and Colorado in 2012, Oregon in 2013, and Colorado in 2015. They combined air quality measurements, a forecasting model, and satellite data to monitor where smoke most heavily affected air quality in these states during wildfires.

The researchers compared the number of doctor visits related to respiratory problems and inhaler prescription refills when smoke was in the air with the number of visits on days without smoke. They found a link between these numbers and the concentration of heavy smoke particulates.

The team found evidence that wildfire smoke increased asthma cases in both Washington and Oregon in 2012 and 2013, respectively. An increase in smoke of 10 micrograms per cubic meter was associated with a 9.5% increase in the rate of asthma admissions in hospitals and urgent care clinics.

"Ten micrograms per cubic meter [of smoke] is on the edge of whether or not you can see it," said O'Dell. "Even I have looked outside, and it looks hazy in the summer, and I think, 'oh, it's foggy.' But then I'll go look it up because that's what I do." According to O'Dell, smoke levels around 20 or 30 micrograms per cubic meter are more visible.

Distant Wildfires, Local Impacts

Colorado served as a special case for O'Dell and her colleagues. Local fires plagued the state in 2012, including one near O'Dell's department at Colorado State University. A few years later, the area was hit by smoke from distant fires in the Pacific Northwest.

When the researchers analyzed the risk statistics for respiratory disease in both of these seasons, they found a surprising decrease in asthma risk from local fires. But they still saw an asthma risk increase from faraway fires in 2015, similar to what they'd seen in Washington and Oregon.

"Potentially, people know when there are local fires; 'I can see the fire and the smoke, so I'm going to stay inside,'" O'Dell said. "Whereas in 2015, smoke is coming from further away, so you might not even notice."

The reason for this unexpected result is still an active area of research, but the team faces challenges. Fort Collins is mountainous, which makes it difficult for satellites and models to estimate smoke from fires in the area, according to O'Dell. Wildfire smoke from far away, however, is more diffuse and easier to track.

The next steps for O'Dell and her colleagues involve communicating fire risk to the public. The research team has already set up a beta version of a website that could act as a "daily smoke forecast." It estimates asthma risk during prescribed burns and wildfires on the basis of the data they have collected so far.

By **Erin I. Garcia de Jesus** (eringarc@ucsc.edu; @viruswhiz), Science Communication Program Graduate Student, University of California, Santa Cruz

Magnetic Surveying Reveals Hidden Ancient Structures

Archaeologists often search for ancient buildings that are buried without a visible trace on the surface. Members of a magnetic surveying group have found a way to address this issue, applying their expertise to help archaeologists search for buildings at the ancient Saudi Arabian city of Thaj.

Thaj is believed to have been occupied between the 3rd century BCE and the 4th century CE. An ongoing archaeology project started investigating the site in 2016. The archaeologists knew the location of the city, but the internal layout of some of the city is hidden, making it difficult to determine the most productive places to excavate. Despite the lack of visual clues, the limestone buildings in the city subtly distort Earth's natural magnetic field. Magnetic surveying techniques can use these distortions to provide a glimpse of the structures hidden underground.

Jérôme Rohmer, an archaeologist working on the Thaj project, contacted the magnetic surveying group led by Marc Munschy. This group is a part of the Géologie Océans Lithosphère Sédiments team at the Institut de Physique du Globe de Strasbourg in Strasbourg, France. Although Munschy and his team do not specialize in archaeology, the techniques for detecting magnetic anomalies that they use can help with a variety of applications—detecting unexploded ordnance, for example—so they decided to take on this new challenge.

Munschy and his group were confident that they could accurately measure the magnetic fields, explained team member Paul Calou, but the type of site determines what data the group obtains and how to interpret them. Calou, a Ph.D. student at the institute, helped conduct the research and presented the research at a poster session in December at AGU's Fall Meeting 2018. "So when someone calls and asks, 'Can you come and check?' we don't really know what it will be," he added. However, a member of his group had previously investigated a site with similar limestone constructions, so they were optimistic that they could get good results in Thaj.

Mapping Magnetic Fluctuations

The group uses a custom-designed system with four magnetometers that can be worn as a backpack. The sensors that the scientists use are lightweight and energy efficient but can introduce distortions from the equipment itself in addition to those from the environment, such as magnetic fluctuations from the Sun. To adjust for these errors, they first use models to correct for the magnetic fields that are known to be produced by Earth or nearby geological features. Then they have to find an area of the site without large magnetic disturbances and perform a 360° sweep to collect data for determining the necessary corrections for any systematic errors from their detectors.

Calou said that sometimes walking back and forth to collect the data in Thaj was boring. However, the occasional spider and scorpion sightings livened things up. "There was a spider that was looking for shade" that began following them to stay in the shade they created, said Calou.

Revealing the Ancient City

The survey team members analyzed the processed data for straight lines or patterns that seemed likely to be signs of human creations. In Thaj, they found lines that represent limestone used in the walls and buildings of the city. One area they surveyed contained an unusual number of distortions. Excavating that area revealed the source of the distortions: a large amount of metal surrounding an ancient forge.

The archaeologists combined the data from the magnetic survey with aerial photography to produce a map of the ancient streets.

By **Bailey Bedford** (baileybedford42@gmail.com; @BBedfordScience), Science Communication Program Graduate Student, University of California, Santa Cruz

Rozan Alkhatib-Alkontar surveys a patch of ground at the site of the ancient city of Thaj, Saudi Arabia, with a lab-made system for measuring magnetic fields. Anomalies in Earth's magnetic fields provide clues to buried archaeological artifacts, a new study shows. Credit: P. Calou

Handling the Kīlauea Eruption's Media Frenzy

A fountain of lava from Kīlauea's fissure 8 in May 2018. Credit: iStock.com/Frizi

One hundred in 1 month: That's how many interviews volcanologist Ken Rubin and his colleagues at the University of Hawai'i gave during the Kīlauea volcano eruption in May 2018.

Rubin was working as a professor of Earth science in Honolulu, Hawaii, when, in April, magma supply increased to the volcano, causing an upper lava lake to overflow. Earthquakes followed, changing the plumbing of the volcano, and the magma drained out of the primary vent. The eruption had begun.

Over the next 4 months, 20 eruptive fissures opened in the area, some of which led to hundreds of homes being destroyed. The event was a focus of national and international news, and as the crisis escalated, misinformation started to fly.

Rubin and his colleagues volunteered to be available for media interviews while geologists at the Hawaiian Volcano Observatory were busy monitoring the situation. Last December, Rubin gave a presentation at AGU's Fall Meeting 2018 detailing what he learned from stepping into the media spotlight.

Challenges to Expect

- People want immediate access to information in the 24-hour news cycle. "The public has an expectation of that right now," Rubin said. But agencies like the U.S. Geological Survey (USGS) aren't always equipped to communicate so frequently. "The USGS puts out awesome products," he said, "but they come out once a day, and that's just too slow in an event like this."
- Without continuous information coming from official channels, citizen scientists and local news channels fill the void. That's how people found out about the start of the eruption, said Rubin: from a drone video of a fissure taken from a resident's backyard and posted to social media. News organizations can pick up these sources and distribute them, for better or worse.
- Unofficial sources can lead to exaggerated or misconceived news. The most doomsday rumor flying around during the Kīlauea eruption, Rubin said, was the idea that half of Kīlauea was going to break off into the ocean and cause a tsunami that would wipe out the west coast of the United States. "There is no evidence in the geological record that this has ever happened," Rubin noted. Other myths included refrigerator-sized lava bombs and acid pouring into the ocean from the volcano.

The event was a focus of national and international news, and as the crisis escalated, misinformation started to fly.

Offering Your Expertise

What is a researcher to do, knowing the media landscape today? Rubin offered this advice:

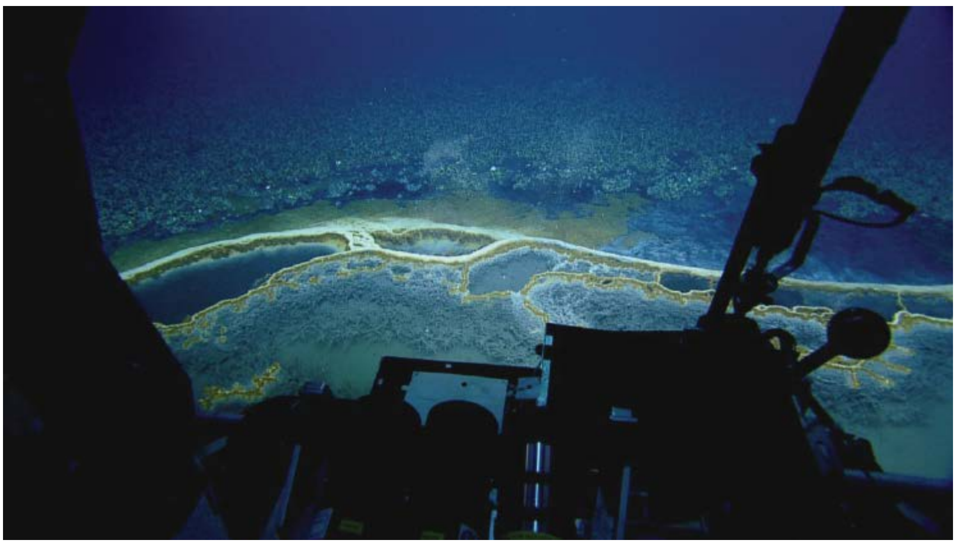
- Provide historical context. The most recent event at Kīlauea is part of a continuous eruption that started in 1983. "None of these hazards were new to this event," Rubin said. "They've happened multiple times over the 35-year history of the eruption." To illustrate this, he created maps of past lava deposits to give historical perspective.
- When possible, push content as much as possible out on social media. Rubin put the historical maps out on his social media, and his posts were often picked up by news organizations, which he could reference during live interviews.
- Put parameters around the real danger of the situation. "Despite most of what you heard from the national and international media, that the hazards were very widespread, they were extremely local," explained Rubin. "It really only impacted people in the immediate area." People who were harmed, such as one man whose leg was broken from a lava bomb, had not followed evacuation orders.
- Understand that debunking misinformation will be a huge part of your job. "A lot of the role of a knowledgeable scientist is to debunk these bizarre theories while being interviewed live in real time by CNN," Rubin said. Keep tabs on the present rumors and prepare a response.
- Make a script and stick with it. Rubin and his colleagues created daily scripts for speaking with the media.
- Have endurance. "It is a pain in the butt," Rubin said. Journalists will call "at all hours," he said, and often one interview will bring an onslaught of new calls. Respond quickly to requests, but also learn to set boundaries.

Rubin ended his talk with a call to researchers to step up to the plate when events demand their expertise.

"Having knowledgeable scientists involved in the information flow is the only way, in my opinion, to help keep the misinformation to a minimum," he said.

By **Jenessa Duncombe** (@jrdscience), News Writing and Production Intern

Waves of Deadly Brine Can Slosh After Submarine Landslides



A remotely operated vehicle explores brine pool formations in the Gulf of Mexico. Credit: Ocean Exploration Trust/Nautilus Live

Far out of sight at the bottom of the Mediterranean Sea, the Red Sea, and the Gulf of Mexico lurk rare features known as brine pools. These basins of extremely salty, nearly oxygen-free water can be a death trap to unsuspecting animals like eels, crabs, and mussels that wander into these "underwater lakes."

Now researchers studying a brine pool at the bottom of Orca Basin in the Gulf of Mexico have shown that submarine landslides can generate massive waves of brine within pools. These tsunami-like events can send deadly brine spilling out into adjoining basins.

Half a Million Tons per Year

A team of scientists led by Derek Sawyer, a marine geologist at The Ohio State University in Columbus, has spent the past year studying Orca Basin, a feature about 350 kilometers southwest of New Orleans, La. They focused on the brine pool at its bottom, which is 123 square kilometers in area—about twice the size of Manhattan—and one of the world's largest.

At about 8,000 years old, this brine pool is fed by an outcropping of salt dating to the Jurassic period. As seawater dissolves this salt, the resulting brine flows downhill because of its high density and pools in the lowest reaches of Orca Basin. This process is ongoing: Researchers have estimated that 500,000 metric tons of salt dissolve per year.

The brine pool is already about 8 times saltier than normal seawater, and it will only grow larger and saltier over time, Sawyer explained. His team studies brine pools because of their parallels to conditions in other times and places: Modern-day brine pools are probably good analogues for conditions on early Earth, and pools might also provide a toehold for life on other planets.

> The tsunami-like events can send deadly brine spilling out into adjoining basins.

Sawyer and his colleagues examined Orca Basin's brine pool, 2,200 meters below sea level, using detailed maps of the seafloor and subsurface imaging. These data were collected, in part, by energy companies looking for oil and gas deposits in the Gulf of Mexico.

Salt Tectonics

The researchers found evidence that multiple underwater landslides had hit the brine pool in the past: Scarps dot the edge of Orca Basin, debris like large boulders litters the bottom of the brine pool, and a sediment core drilled in 1983 revealed a 16-meter-thick landslide deposit.

These landslides were likely caused by "salt tectonics," Sawyer and his team proposed. Bodies of salt under the seafloor can move and flow over time, eventually pushing up on the seafloor, Sawyer said. "It's like stepping on a tube of toothpaste." Over time, this motion can build up the angle of the seafloor and create steep slopes susceptible to landslides. In Orca Basin, slopes as steep as 22° have been recorded—that's about 6 times steeper than the maximum permissible road grade on U.S. highways.

Laboratory experiments have shown that fast-moving sediments striking a dense fluid such as a brine can trigger large waves. But just how large?

Using estimates of landslide speed based on the timing of telegraph cable breaks after an underwater landslide in 1929, the density difference between seawater and brine water, and other parameters, Sawyer and his team calculate that wave heights ranging from 90 to 360 meters could slosh through Orca Basin's brine pool following a landslide.

These amplitudes are far larger than normal waves and rival only the largest historical tsunami, Sawyer noted.

Overspill

Landslide-induced waves in Orca Basin are large enough to potentially overspill the basin, Sawyer and his colleagues concluded: The lowest spill point of Orca Basin is only 139 meters above the surface of the brine pool.

"It's not unreasonable" that brine might make it over this spill point and escape into adjoining basins, said Sawyer. That would certainly be bad news for sea creatures living nearby. "If the brine gets sloshed on them, it's not going to be a nice day for them," said Sawyer. These results were published in January in *Scientific Reports* (bit.ly/brine-pools)

These results are "very interesting," said Erik Cordes, a biologist at Temple University in Philadelphia, Pa., not involved in the research. "Brine would likely cause a significant die-off of the animals that it came in contact with further downslope."

Age dating the landslides that have occurred in Orca Basin would help pin down how often brine gets tossed into surrounding ecosystems, said Sawyer. "I'd love to get some more cores."

By **Katherine Kornei** (hobbies4kk@gmail.com; @katherinekornei), Freelance Science Journalist

D.C. Leads Way with Landmark Clean Energy Law

On 18 January 2019, Washington, D.C., mayor Muriel Bowser established the city as a global leader in clean energy and efforts to combat climate change.

The Clean Energy DC Omnibus Amendment Act of 2018 mandates that 100% of the electricity sold in the city come from renewable energy sources by 2032. In addition, the bill, which was signed into law at AGU Headquarters, doubles the required amount of solar energy deployed in the District, makes significant improvements to the energy efficiency of existing buildings, provides energy bill assistance for low- and moderate-income residents, requires all public transportation and privately owned fleet vehicles to become emissions-free by 2045, and funds the DC Green Bank to attract private investment in clean energy projects.

At the bill's signing ceremony, Bowser said that if the country is going to make progress on addressing climate change, cities and states need to lead the way.

Bowser also took a swipe at the Trump administration plan to withdraw the United States from the Paris climate accord. "We have in the last two-and-a-half years been called upon to lock arms with each other to protect our values. And it is a D.C. value that we care for the Earth, our environment, and we recognize that we are indeed stewards for the next generation of Washingtonians and Americans and people of the world," Bowser said.

"We are our nation's capital, and it is our faces that we want the world to know as Washington, D.C., not those faces," she said, distinguishing the city from the Trump administration. "That's why we will continue to acknowledge that climate change is real, that we believe science, and that we will do all we can to make the world and our city a better place."

Bowser and others at the signing pointed to AGU's headquarters, the first net-zero building renovation in the District, as an example of meeting energy goals in combating climate change. AGU CEO and executive director Chris McEntee welcomed the mayor, saying that it was an honor for the signing to take place at the new building "as the District steps forward to be a leader on renewable energy that the rest of the nation and the world can follow."

Leading on Fighting Climate Change

The clean energy law is important "because it's about the future," Washington city council member Kenyan McDuffie told *Eos*. "It is about the generation that's coming up behind us. It takes cities like the District of Columbia to lead the way, particularly when the federal government doesn't," said McDuffie, who was instrumental in shepherding the bill, which the city council unanimously approved.

Mayor Muriel Bowser signs clean energy legislation at AGU Headquarters on 18 January. Others in the photo include Mike Tidwell, executive director of the Chesapeake Climate Action Network (left); Washington, D.C., city council member Mary Cheh (fourth from left) next to city council members Jack Evans and Kenyan McDuffie; and AGU CEO and executive director Chris McEntee (right). Credit: Beth Bagley

Advocacy Group Perspective

The mayor "is signing the strongest climate legislation of any state in the United States," said Mike Tidwell, executive director of the Chesapeake Climate Action Network, which played a lead role in advocating for the law. Tidwell said that D.C. should be considered a state and that its population is bigger than several states.

The law, Tidwell told *Eos*, "is not only good for the people who live here—cleaner air, less impact on the climate—but it sets an example for other states of what can be done. We brought everyone together, we worked out all of our differences within the environmental community, the economic justice communities, the business community, and we passed the strongest climate bill in the nation."

Howard Crystal, senior attorney with the Center for Biological Diversity's Climate Law Institute, told *Eos* that he hopes that implementation of the law goes smoothly. "Unfortunately, the fossil fuel industry and other interests vested in the current energy system will not go quietly into the night. While this is an incredible step forward, I'm sure there will be efforts to undermine it. But I'm also confident that the incredible activism that got this bill passed will ensure that if changes are made, [they will be] to further strengthen the law and not to weaken it."

Support from the Business Community

Marc Battle, vice president of government and external affairs with the Potomac Electric Power Company in Washington, D.C., told *Eos* that the law is "very important" and that the energy company is "very happy to be supportive" of it. The law "establishes the District of Columbia as a leader in fighting climate change and reducing carbon and making our city and our world a better place."

The biggest hurdle to achieving the goals of the law is "ensuring that there is sufficient renewable energy to supply D.C. by the deadline that we set for ourselves," Battle said. "The District is a small place. We don't have room to expand. There is a limited area for rooftop solar deployment. So we really have to get creative in how we roll out renewable energy to make sure that we hit our goals."

"What this bill really means is that we are starting the hard part of the District doing its part to reduce carbon emissions so that we can say to the rest of the planet that we are trying to do it and here is how we are doing it," Chris Weiss, executive director of DC Environmental Network, told *Eos*. "What's really important is that we will 3 or 4 years from now know how far we are toward putting the policies in place to make those carbon reductions happen."

By **Randy Showstack** (@RandyShowstack), Staff Writer

One-Pixel Views Show Earth as an Exoplanet

An image of Earth captured by the DSCOVR satellite. Credit: NASA/DSCOVR

When Al Gore, then U.S. vice president, originally proposed the Deep Space Climate Observatory (DSCOVR) satellite in 1998, he hoped that its detailed images of the Earth's surface would inspire the public. They have, and now scientists are finding a novel use for these satellite observations that Gore probably never imagined: studying exoplanets. By averaging thousands of high-resolution DSCOVR images down to just one pixel each, a team of scientists was able to determine how the Earth's average color varies over a year. The team also compared the data with models of the Earth to reveal how environmental conditions like clouds and snow modulate the appearance of distant exoplanets. These results were presented in January at the 233rd Meeting of the American Astronomical Society, held in Seattle, Wash.

Smashing the Data

Aronne Merrelli, an atmospheric scientist at the Space Science and Engineering Center at the University of Wisconsin–Madison, and his colleagues collected over 5,000 images of the sunlit side of the Earth taken in 2016 by the Earth Polychromatic Imaging Camera (EPIC) on board DSCOVR. The researchers repurposed these EPIC data, which were originally intended to reveal information about the planet's ozone levels, aerosols suspended in the atmosphere, clouds, and vegetation. "We just smash it down to one pixel," said Merrelli of the data spanning the ultraviolet, visible, and infrared. "We're throwing away a lot of information." This single-pixel view of the Earth is similar to the resolution scientists have of distant planets orbiting other stars, said Merrelli. "You can mimic what Earth might look like from very far away."

The researchers—a mix of Earth scientists and astronomers—then examined how the planet's average color varied over seasons. They found that Earth tended to be redder from June through September, probably because of the increase in vegetation in the Northern Hemisphere and a reduction in snow cover.

The Importance of Clouds

Merrelli and his team also compared the EPIC observations with a model of the Earth's surface with its current configuration of landmasses and oceans and varying amounts of clouds, snow, and sea ice. These simulations allowed the scientists to determine the impact of dynamic environmental conditions on the planet's color. They found that clouds played a large role in dictating the planet's average color.

Drake Deming, an astronomer at the University of Maryland not involved in the research, said, "This type of investigation definitely lays the groundwork for imaging of Earth-like exoplanets."

By **Katherine Kornei** (hobbies4kk@gmail.com; @katherinekornei), Freelance Science Journalist

The Mars Anthropocene

The impact of human activities on Earth serves as the basis for defining a new geological time interval on our planet: the Anthropocene. If the pace of current efforts to send humans to Mars is any indicator, the impact of human activities may soon be as quantifiable on Mars as it is on Earth, and the Anthropocene could soon make its debut as the first multiplanetary geological period.

The Anthropocene epoch, proposed as a new post-Holocene geological time interval beginning sometime in the mid-20th century, is not yet a formally defined geological unit within the terrestrial geological timescale. However, the term has seen widespread usage in the scientific and popular literature, as well as in the media, since it was popularized in 2000. It is characterized by the way in which human activities have profoundly altered many geologically significant conditions and processes, leaving characteristic evidence in the Earth's stratigraphic record (Table 1).

During the next few decades and for the first time in history, the impact of human activities and technologies not only on Earth but also on other planetary bodies could be analyzed and quantified. It is probably still too soon to propose a new epoch defining the geology of other planets based on the impact of human activities, but we may start considering the case of Mars.

Explorers on Mars extract water from subsurface ice deposits in this artist's rendering. Credit: NASA Langley Advanced Concepts Lab/Analytical Mechanics Associates

So far, exploration of Mars has been carried out by robotic explorers, which have likely left little lasting impact, and this impact has not been on a global scale. But a fundamental change is already in motion: NASA has been officially commissioned to send humans to Mars. Other national and private-sector space programs have launched their own efforts, so it is entirely possible that one of these other organizations may precede NASA in completing manned missions to Mars.

Table 1. Signs of Human Impact on Earth and Potential Impacts on Mars

PARAMETER	EARTH (OBSERVED)[a]	MARS (FORECASTED)
Uniqueness	Human impact signatures are sufficiently different from the natural features of the Holocene to constitute a new unit of geological time.	Humans will leave stratigraphic signatures (buildings, evidence of atmospheric changes, biomass) in sediments and ice never seen before on Mars. Except for ice ages, human colonization will be the first global change on Mars since the atmospheric loss billions of years ago.
Global extent	Human signatures show excellent global or near-global correlation in a wide variety of marine and terrestrial sedimentary bodies.	In situ resource utilization and microbial dispersion will be global because raw materials (potentially mined) and ice (potentially biocontaminated) are globally distributed.
Preservation potential	The archaeological record registers new patterns within the Earth system.	There will be higher preservation potential than on Earth because the thinner atmosphere and lack of an active microbiota retard alterations to the record of human effects.
Synchronous base	All the above effects are globally synchronous stratigraphic markers for the Anthropocene, starting in the mid-20th century.	All the stratigraphic markers will develop at the same time, once humans begin settling bases on Mars.

[a]Earth parameters are after *Waters et al.* [2016]

Therefore, it is possible that human activities will soon inaugurate an Anthropocene on Mars. Like the Anthropocene on Earth, this new era would be distinguishable by markers in the planet's stratigraphic record.

Planning Our Arrival

The coming era of space entrepreneurship will determine the timeline of human activity on Mars, especially since NASA adopted a decentralized market approach in 2005, awarding contracts to private players. Since 2005, three quarters of the growth in the global space economy has come from commercial endeavors. The company SpaceX has stated that it could land humans on Mars in the next 10–12 years, and it has partnered with NASA in the landing site selection process through the Space Act Agreements.

Plans are also on the table to start revisiting the Outer Space Treaty, an agreement put forth 50 years ago and signed by all the current and aspiring spacefaring nation-states and many others, which provides the basic framework for international space law. An updated treaty should help to lay the basis for human settlement on Mars and to expand commerce in the age of space entrepreneurs. The human presence on Mars is likely to be a reality all too soon, despite the lengthy list of knowledge gaps that we need to address to start understanding the anthropogenic impact on Mars's geologically significant conditions and processes.

Microbial Hitchhikers

What we already know is that the moment astronauts set foot on Mars, microbial contamination will be inescapable and irreversible. Astronauts staying there for the long term would require some means of transporting and storing water and food, a continuous air supply, and the containment and management of secretions and human waste, among other requirements.

> All the anticipated impacts derived from human exploration will happen long before we begin to alter Mars on a planetary scale.

These activities would create an unavoidable risk of microbial leaks from spacecraft, space suits, and waste disposal systems. The microbial leaks and species invasions could spread far enough to produce a global impact on Mars, eventually creating identifiable sediments.

Human habitat modules and rovers would continuously release microbes into the environment. Furthermore, astronaut bases established in the planet's subsurface to protect their human occupants against radiation and extreme temperature fluctuations would also shield their microbial occupants from the naturally sterilizing conditions of the surface radiation and oxidative environment.

Human Activities' Mark on the Martian Landscape

Searching for resources on Mars—and using those resources in situ—would also add to the human effects on Mars. Extracting and processing Martian raw materials to obtain life-supporting consumables and propellants would transform the Martian surface and subsurface and imprint a permanent mark. Human topographic signatures would start to accumulate, beginning with such small-scale effects as regolith erosion, landslides, and terrain collapse and eventually extending to larger areas: flattening mountains, piling hills, or excavating major open-pit mines.

Some of these human activities would potentially generate new zones where terrestrial organisms are likely to replicate and where any extant Martian life could flourish. Life as we know it requires water, so these zones could appear, for example, after drilling to explore a subsurface aquifer.

A third possible aspect of the Mars Anthropocene, beyond the release of microbes and land surface changes in the course of in situ resource use, is the creation and wide distribution of novel materials, including pollutants. A Martian field station with a four-person crew, for example, would require significantly more electrical power than our current robotic missions. Using nuclear power to meet these needs could create long-lived radioactive waste. Also, if a reactor were to explode while operating or be destroyed during a failed atmospheric entry, it could disperse a radioisotope signature over a wide area.

Making human life possible on Mars will require significant and unprecedented modification of the Martian landscape and skyline (Table 1). Predicting and understanding how these changes may occur on Mars—and gaining insights into the dynamics and sensitivity of landscapes and their responses to human forcing at global scale—will be central to interpreting and mitigating our impact on the planet.

Table 2. Arguments for the Existence of an Earth Anthropocene Compared with Projected Human-Generated Changes to Mars

PARAMETER	EARTH (OBSERVED)	MARS (FORECASTED)
	Atmospheric Changes	
Composition	black carbon, inorganic ash spheres, and spherical carbonaceous particles from fossil fuel combustion; elevated carbon dioxide and methane concentrations	rocket fuel emissions that will include aluminum oxide particles and gaseous chlorine species; residues from life sustainment systems, human bases, and greenhouses
Temperature	average global temperature increase of 0.6°C–0.9°C from 1900 to the present	local hot spots, eventually transitioning to global effects if terraforming starts
	Geological Changes	
In situ resource use	mining, industrial activity	mining
Distribution of novel materials	"technofossils": elemental aluminum, concrete, plastics	"technofossils": elemental aluminum, concrete, plastics
Pollutants	polycyclic aromatic hydrocarbons, polychlorinated biphenyls, pesticides, leaded gasoline; artificial radionuclides from thermonuclear weapons tests	residues from human bases and vehicles, long-lived nuclear wastes; widely dispersed radioisotope signatures from reactor failures
	Biological Changes	
Extinction of species	extinction rates far above background rates since 1500; deforestation	risk of extinction of any extant microbiota on Mars
Species invasions	human-triggered transglobal species invasions	microbial leakage from astronauts and human bases (if Mars has always been lifeless, these would be the first organisms on the planet)
Farming	changes associated with agriculture and fishing	first greenhouses on Mars

Building Colonies Increases the Impact

A variety of human activities define the Anthropocene on Earth. Such activities include changes in erosion and sediment transport and alterations in the chemical composition of soils and the atmosphere associated with colonization, agriculture, and urbanization. Human activities alter Earth's carbon cycle and the cycles of various metals through the environment. Humans also introduce nonnative and invasive species into new habitats.

As humans begin to colonize Mars, similar changes can reasonably be anticipated to occur there at a rapid pace (Table 2). These changes are likely to produce a stratigraphic signature in sediments and ice that will be distinct from that of the Late Amazonian, the current time period on Mars (Figure 1).

We have already witnessed a similar process in Antarctica, where analogue studies make use of the continent's climate, terrain, and isolation to simulate conditions and processes that humans will likely face on missions to Mars. Although humans in Antarctica are mainly devoted to scientific research and they must follow a determined policy for environmental conservation, the effect of the "age of humans" is already visible on the continent, creating a pressing concern.

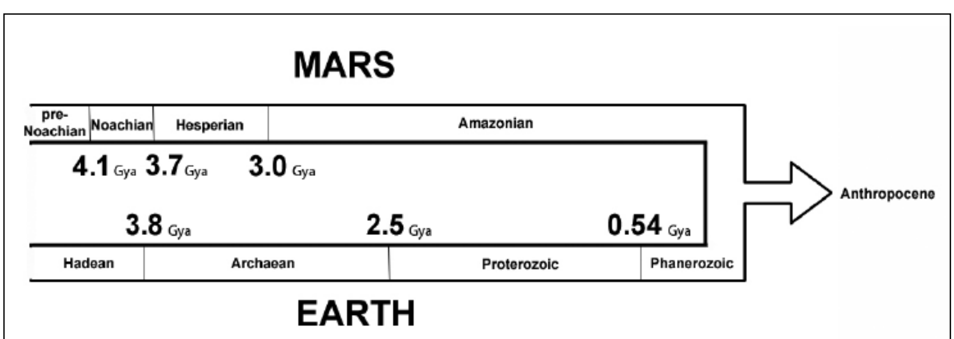


Fig. 1. Could geological timescales on Earth and Mars converge into one common Anthropocene future?

Effects Begin on Day One

Given that humans have yet to set foot on Mars, it seems like we have plenty of time to think about ways to manage our impact on the planet. However, all the anticipated impacts derived from human exploration will happen long before we begin to alter Mars on a planetary scale.

At our current rate of progress, these large-scale endeavors are just one step above science fiction. Today's reality is that our children or grandchildren will see astronaut footprints on the red sands of Mars. And when that happens, the Mars Anthropocene will begin.

Acknowledgments

The research leading to these conclusions is a contribution from the project icyMARS, funded by the European Research Council, Starting Grant 307496.

References

Waters, C. N., et al. (2016), The Anthropocene is functionally and stratigraphically distinct from the Holocene, *Science, 351*(6269), aad2622, https://doi.org/10.1126/science.aad2622.

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Erupting Volcanos Liven Up Your Game Night

Hikers in National Park Adventure can choose to help park workers remove invasive species from a national park and learn about environmental management. Credit: EarthGames

Looking for fun and educational games to play with your friends and family? We've got you covered. These games, designed by scientists and educators, teach people of all ages about planetary science, environmental conservation, and natural disaster preparedness. Some games are still in development, so keep an eye out for them in the next year.

Where's Water?

This deck of cards trades hearts, diamonds, spades, and clubs for planets, moons, and asteroids to teach where water has been found in the solar system. One side of the cards shows a high-resolution image of a solar system body, its gravity compared with Earth's, its location in the solar system, and whether it's made of rock, gas, or ice. The backs of the cards show what type of water reservoir exists on that object and how much water the reservoir has. The 40-card deck, called Planetary Cards (bit.ly/planetary-cards), was designed by a collaborative team of planetary scientists and educators.

The cards come with a rule book of games. Players can learn about relative gravity and water content across the solar system in a game of Accretion. Build the Solar System teaches about which objects are neighbors; Crazy Earth shows what the various planets, moons, and asteroids have in common; and Planetary Rummy tests players' knowledge of each of these planetary properties.

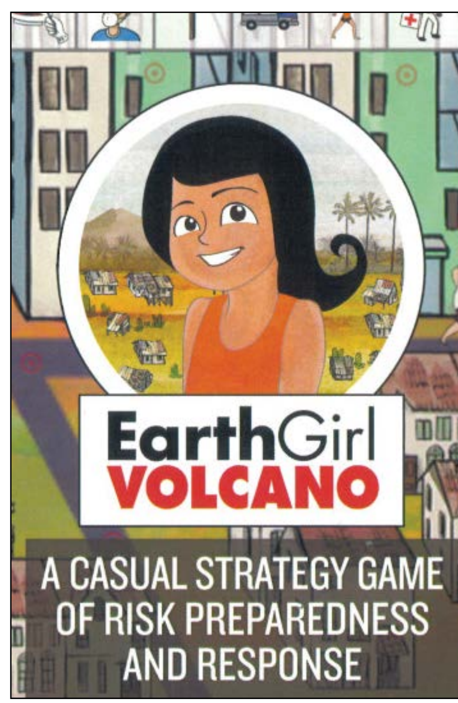
Among many other solar system locales, water can be found on Earth, Enceladus, Saturn, Mars, and Titan, which are seen here on Planetary Cards. Credit: Kimberly M. S. Cartier

Earth Girl to the Rescue

Help save a town from a volcanic eruption before a disaster strikes in Earth Girl Volcano (earthgirl2.com). This strategy game teaches about volcano risk, disaster management, and preparedness in scenarios inspired by real-life communities next to the Pacific Ring of Fire. Players can pick from small villages, populous towns, and industrial parks. They design disaster mitigation strategies by assessing danger areas, educating the population, building infrastructure, or introducing new technologies.

After saving virtual communities from eruption, ashfall, mudflows, and burning clouds, players can prevent more disasters in two other games in the series. Children of all ages can strategize to help a coastal community survive a deadly tsunami in Earth Girl Tsunami (bit.ly/earth-girl-tsunami) and become superpowered disaster heroes in Earth Girl: The Natural Disaster Fighter (earthgirlgame.com).

All three games are freely available for download in multiple languages on tablet platforms, desktop computers, and laptops.



Play as Earth Girl to save people living near the Ring of Fire from the hazards of volcanoes in this video game by the Earth Observatory of Singapore.

Become a Deputy Park Ranger

Journey through a forested national park in National Park Adventure (bit.ly/nature-bridge), a Web-based interactive computer game. Players explore trails and learn about the plants, animals, and land in the park. They discover how national parks help preserve cultural and historical locations and realize how climate change is affecting the country's outdoor environments.

The EarthGames group at the University of Washington in Seattle developed the game to be played by students before they visit a park and also to make national park experiences available to those who cannot access a park.

Minigames and side quests peppered throughout the game teach valuable outdoor skills like how to pack, read a compass, and follow a trail map. Players identify and weed invasive plant species, thin a forest before a beetle infestation, and practice how to respect the environment inside a national park. After exploring the park, a player will earn Deputy Ranger status and be ready to explore real-world national parks.

A park ranger welcomes you and your friend at the start of National Park Adventure. Credit: EarthGames

The More Explosive, the Better

Which volcano is most explosive? Most devastating? Tallest, deadliest, or most unpredictable? Test the might of your favorite volcano against your opponent's in Volcanoes Top Trumps (volcanoestoptrumps.org). The game, created by volcanologists, teaches players about plate tectonics and some of the world's most famous volcanoes. The game is playable as a deck of cards or online, and profits go to a research project that aims to improve volcano forecasts.

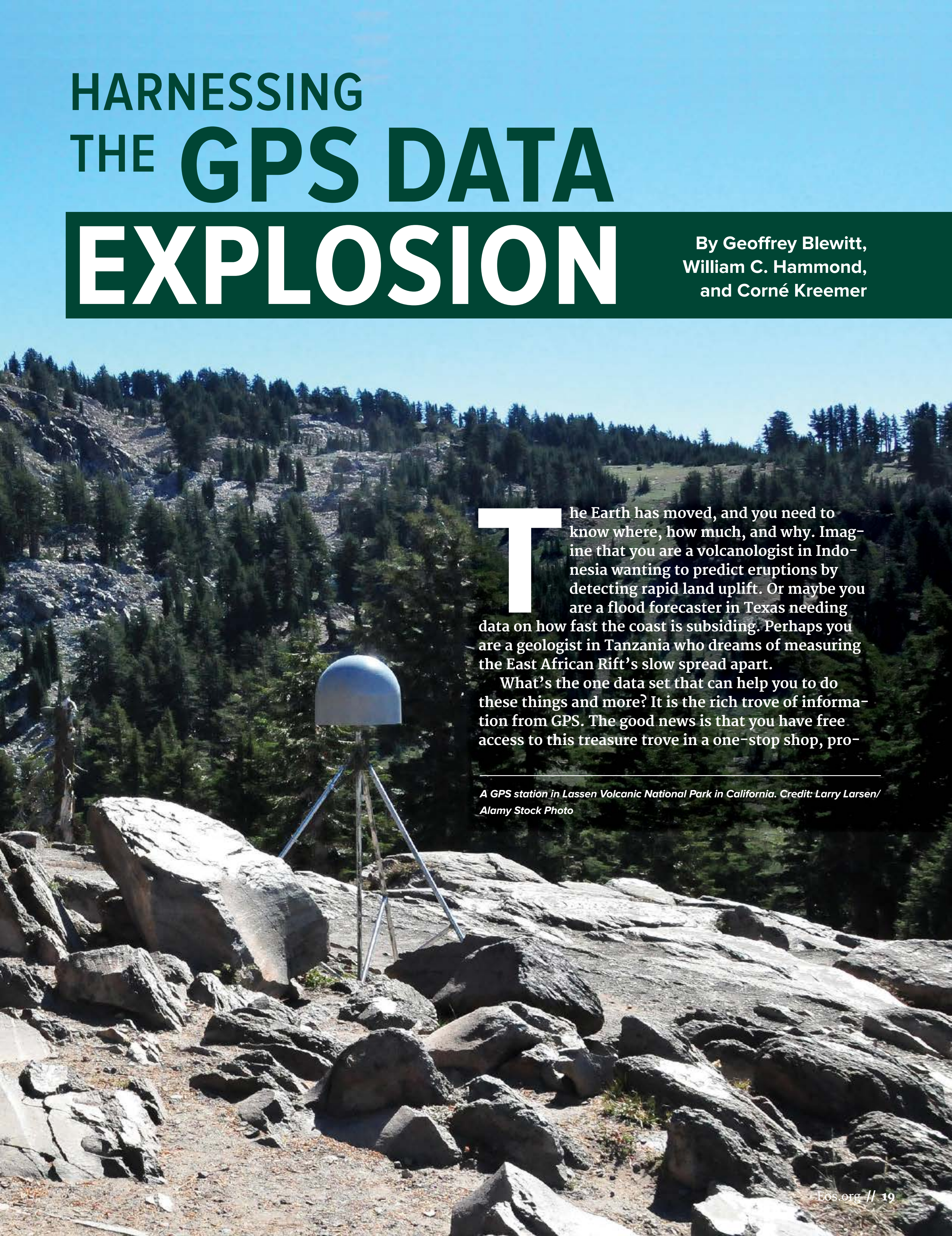
The 30 volcanoes included in the deck represent different styles of eruption, span every continent, and range in activity level. Game cards include an image of the volcano, geologic or historic facts, and game stats to play volcanoes against each other. A volcano's stats are based on metrics determined from real data about a volcano's size, predictability, historical deadliness, explosivity, and potential devastation. The game team's subjective "Wow! Factor" also makes these cards an excellent resource when deciding on your favorite volcano in the annual Volcano Cup on Twitter.

Kick back and enjoy these geobased games that show that education and fun can work hand in hand.

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

HARNESSING THE GPS DATA EXPLOSION

By Geoffrey Blewitt, William C. Hammond, and Corné Kreemer



The Earth has moved, and you need to know where, how much, and why. Imagine that you are a volcanologist in Indonesia wanting to predict eruptions by detecting rapid land uplift. Or maybe you are a flood forecaster in Texas needing data on how fast the coast is subsiding. Perhaps you are a geologist in Tanzania who dreams of measuring the East African Rift's slow spread apart.

What's the one data set that can help you to do these things and more? It is the rich trove of information from GPS. The good news is that you have free access to this treasure trove in a one-stop shop, pro-

A GPS station in Lassen Volcanic National Park in California. Credit: Larry Larsen/ Alamy Stock Photo

Artist's impression of a GPS Block IIF satellite, one of the newest GPS satellites in orbit. Credit: NASA

vided by the Nevada Geodetic Laboratory (NGL; bit.ly/Eos_NGL).

NGL takes raw GPS data from more than 17,000 stations around the globe and makes data products that are multipurpose. For example, the same data can be used to study the tectonics of continental rifting and to improve the global reference frame for studies of global sea level change.

Anyone can access all these data through our portal. But we recognize the sheer volume. We recognize that the sheer volume of the total set of GPS data is overwhelming, so we've built an interface that lowers the barrier to participation by novice users of GPS data and allows them to pursue their own investigations.

Geodesy and Beyond

Thanks to a series of innovations and exponential growth over the past 3 decades, GPS has become an important tool for geodesy and geophysics, pushing forward the science and precise measurement of the Earth's various active processes. GPS now forms an integral component of the newest generation of Earth science and natural hazard assessment capabilities for monitoring and understanding earthquakes, tsunamis, volcanoes, mountain growth, aquifers, sea level, glaciers, ice sheets, mantle flow, terrestrial water storage, and water vapor, to name a few.

The field of geodesy—which measures the size, shape, gravitational field, and spin of the Earth and how they all change over time—was the first to use GPS for science. In fact, geodesy had been instrumental in improving GPS data analysis that enables pinpoint positioning using high-precision equipment. But now the scope of applications is broadening rapidly.

We are witnessing an exponential explosion in the number of geodetic-quality GPS stations around the globe, in the amount of data collected, and in the quantity and variety of data products for scientific applications. This explosion is both a cause and an effect of scientists' starting to use GPS data from many traditionally nongeodetic disciplines. Moreover, feedback from multiple disciplines leads to improved models of geodetic observables, thus improving GPS data products for all.

Harnessing the data is therefore essential to enabling new applications and discoveries. Doing this requires implementing an operational system that makes it easier for inexperienced users to access the data and conduct their own investigations.

NGL's operational system fills this need. What's more, we foster geoscience collaboration and education by making our GPS data products open access.

A Changing Landscape

In the early days of GPS, geodesists expended enormous effort to improve positioning precision for regional networks of just a few GPS stations. Now we obtain and process data from a global distribution of stations. NGL obtains all the available geodetic GPS data—currently from more than 17,000 stations—to place every observation in the context of every other observation in a global frame of reference aligned with Earth's center of mass.

Managing the resulting flood of data has challenged us to invent new processing strategies, automatic systems, algorithms, and robust estimation techniques. Our system now produces, and makes publicly available, data products such as position coordinates (latitude, longitude, and height) for all geodetic-quality GPS stations around the globe that are known to us with various data intervals, latencies (lag times between when data are collected and when they are available to use), and reference frames that might be useful to other users.

Hundreds of organizations collect, manage, and distribute the original data from these stations. These organizations cooperate under various service-oriented institutions, such as the International Global Navigation Satellite Systems Service (IGS) and UNAVCO, a university-governed consortium that facilitates geoscience research and education using geodesy.

In total, NGL scours more than 130 Internet archives in an attempt to find all possible useful GPS data so that users need to visit only one access point to get all the data products they require, from the scale of a city to the scale of the entire planet.

An Open-Access Resource

NGL makes its data products available online, including metadata, lists of stations, plots of position coordinates, tables of data holdings, and descriptions of new items relating to the products. Stations in a given field area can be found using a clickable and scalable interactive map. All products are openly available, many as simple text files, allowing data to be accessed automatically and built into an analysis workflow.

Every week, NGL updates the daily position coordinates of some 10,000 stations. Every day, we update 5-minute position coordinates for more than 5,000 stations. Every hour, we update 5-minute position coordinates for about 2,000 stations. These lower-latency products have proved to be useful, for example, for gaining early insight into large earthquakes by measuring permanent coseismic displacements and postseismic displacements caused by fault after-slip and upper mantle relaxation.

NGL also routinely updates station velocities—the speed and trajectory at which stations are moving in the global reference frame—which can be used to image the rates of

We are witnessing an exponential explosion in the number of geodetic-quality GPS stations around the globe.

deformation of Earth's surface for a variety of interdisciplinary applications. These velocities are estimated robustly using the Median Interannual Difference Adjusted for Skewness (MIDAS), a median-based GPS station velocity estimator that is insensitive to outliers, seasonality, step functions (abrupt changes) arising from earthquakes or equipment changes, and statistical data variability [*Blewitt et al.,* 2016]. MIDAS also provides velocity error bars based on subsampling the data that prove to be realistic, for example, when comparing estimated velocities of stations that are close to each other or are separated by a tectonically stable region. Furthermore, documented step functions are made available, with links to known earthquakes and equipment changes.

Expanding Capabilities

The availability of precise GPS data that are dense in space and time is transforming how scientists model and visualize active Earth processes in ways we would never have imagined 3 decades ago.

For example, we recently extended our median-based robust techniques to map motions of Earth's surface from GPS point data [*Hammond et al.,* 2016]. Figure 1 shows the high resolution we can now obtain in the patterns of vertical crustal motion from various processes including glacial isostatic adjustment (GIA), the slow continent-scale relaxation of North America following the Last Glacial Maximum. Images such as this can help to constrain parameters of GIA models [*Kreemer et al.,* 2018].

In this way, such complete automation of the processing of all potentially valuable data into freely available products allows everyone to focus more on discovery and interpretation of the results. This data-rich approach provides greater data redundancy, reproducibility, and statistical significance of scientific findings.

There's more: One person's "noise" may actually be someone else's signal. As a necessary part of accurately determining coordinates of GPS stations, geodesists need to model and estimate variability in atmospheric refraction of the GPS signal, which is strongly influenced by water vapor. Data products derived from these models are useful to scientists for whom atmospheric refraction is a nuisance (e.g., those calibrating satellite radar data). To support research in using these products, NGL recently made a new data product publicly available: the time series of tropospheric refraction parameters (i.e., total zenith delay and 2-D gradient in delay) every 5 minutes starting in 1996 from all available GPS stations.

But this refraction information—a globally and temporally self-consistent data set of 35 million daily station files—provides finely detailed data on the time evolution of atmospheric water vapor. This information, when com-

> Even fundamental physics is fair game, as we collaborate with physicists using the constellation of GPS atomic clocks as a giant dark matter detector.

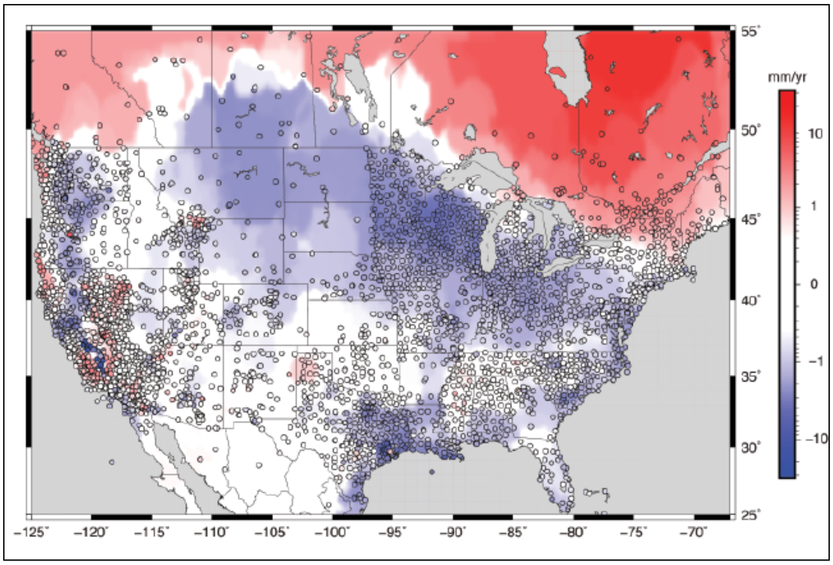


Fig. 1. GPS stations (circles) and observed rate of vertical displacement of continental North America. Glacial isostatic adjustment dominates this displacement: uplift (red) in Canada and subsidence (blue) in the United States. California's Central Valley and the Gulf Coast of Texas and Louisiana exhibit rapid subsidence. White regions are statistically consistent with zero motion with respect to Earth's center of mass. Rates are plotted on a log scale and interpolated using the GPS imaging method of Hammond et al. *[2016].*

bined with other data sets, can help with studies of how climate has behaved over the past 2 decades.

Quality assurance (QA) data are also provided daily for every station on the basis of statistical analysis of the processed data, such as how well models fit the raw observations. Investigators can use QA data to validate data products before they are ingested into geophysical analysis, for example, to identify when GPS data start to degrade because of equipment failure. QA data can also identify which GPS stations provide the highest-quality data and which are subject to such environmental effects as excessive multipath error (caused by reflected GPS signals in the station environment) or sky obstructions.

Benefits of Open Access

The success of this enterprise depends critically on the principle of open availability of GPS data provided by contributing networks. This availability allows us to provide open, online access to the data products. As a result, network operators can see how results from their data compare with those from other networks, and data users can quickly access results without having advanced data processing expertise. This creates a win-win situation for everyone concerned.

Motivated by this, NGL and UNAVCO jointly developed the Plug and Play GPS project (bit.ly/Plug_Play_GPS), funded by NASA's Advancing Collaborative Connections for Earth System Science (ACCESS; bit.ly/Eos_access) program. The goal of Plug and Play GPS is to reduce barriers for less experienced investigators wishing to participate in the geodetic community, for example, by installing new GPS stations in a region currently with sparse coverage, such as Africa. The idea is that any investigator can register a newly installed GPS station and deposit data at the UNAVCO archive, and in return, NGL will process the data and provide the data products outlined above.

In our experience, the capability to process all known data in a robust turnkey fashion enhances opportunities for everyone to make scientific discoveries without necessarily preplanning all of the steps that lead to discovery's door. For example, even fundamental physics is fair game, as we collaborate with physicists using the constellation of GPS atomic clocks (on board GPS satellites) as a giant dark matter detector [*Roberts et al.*, 2017]. The idea is that forces of nature possibly associated with dark matter might affect the highest-precision devices ever invented: atomic clocks. Comparing atomic clocks in space is something GPS has been doing routinely for decades!

The possibilities are seemingly endless. NGL is committed to continuing to provide this long-running service to the scientific community, and we encourage researchers to explore these data sets and apply their creative skills to scientific investigations that have yet to be conceived.

Acknowledgments

This project was funded by NASA grants NNX12AK26G and NNX14AJ52A.

References

Blewitt, G., et al. (2016), MIDAS robust trend estimator for accurate GPS station velocities without step detection, *J. Geophys. Res. Solid Earth, 121,* 2,054–2,068, https://doi.org/10.1002/2015JB012552.

Hammond, W. C., G. Blewitt, and C. Kreemer (2016), GPS imaging of vertical land motion in California and Nevada: Implications for Sierra Nevada uplift, *J. Geophys. Res. Solid Earth, 121*, 7,681–7,703, https://doi.org/10.1002/2016JB013458.

Kreemer, C., W. C. Hammond, and G. Blewitt (2018), A robust estimation of the 3-D intraplate deformation of the North American plate from GPS, *J. Geophys. Res. Solid Earth, 123,* 4,388–4,412, https://doi.org/10.1029/2017JB015257.

Roberts, B. M., et al. (2017), Search for domain wall dark matter with atomic clocks on board Global Positioning System satellites, *Nat. Commun., 8,* 1195, https://doi.org/10.1038/s41467-017-01440-4.

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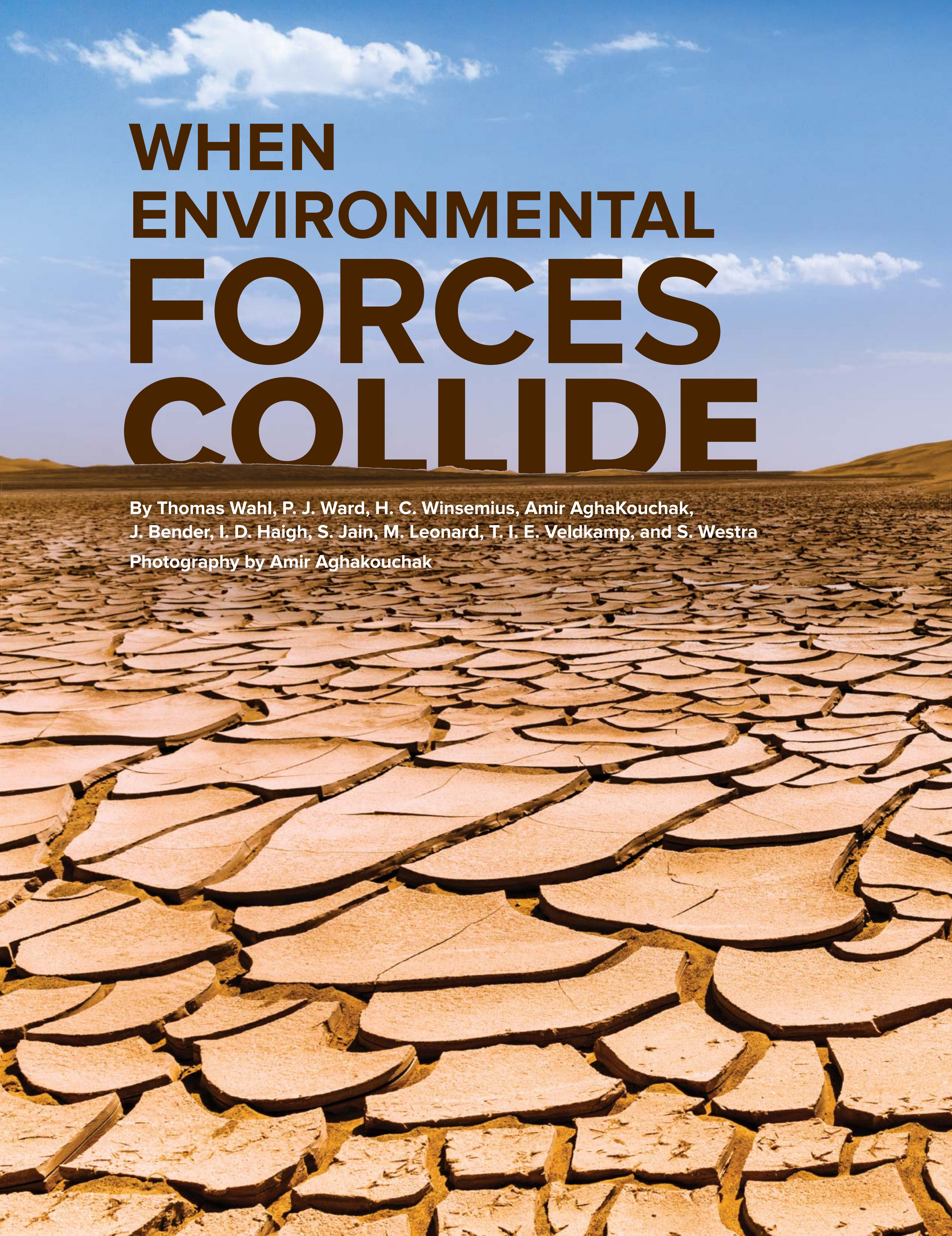

WHEN ENVIRONMENTAL FORCES COLLIDE

By Thomas Wahl, P. J. Ward, H. C. Winsemius, Amir AghaKouchak, J. Bender, I. D. Haigh, S. Jain, M. Leonard, T. I. E. Veldkamp, and S. Westra

Photography by Amir Aghakouchak

In 2017, a combination of unprecedented local rainfall intensities and storm surges from Hurricanes Harvey, Irma, and Maria flooded Houston, large parts of Florida, and numerous island nations in the Caribbean. Such hydrologic compound events—when the combination of two or more hazard events or climate variables leads to an extreme impact—have a multiplier effect on the risk to society, the environment, and infrastructure [*Zscheischler et al.,* 2018].

Hydrologic extremes, such as floods and droughts, are among the world's most dangerous and costly natural hazards. Between 1980 and 2013, flood losses tallied more than U.S. $1 trillion and caused

Spring rains almost immediately evaporate in Iran's Lut Desert, where land surface temperatures have been measured as high as 70.7°C (159.3°F).

Population growth has greatly increased water demand along the Colorado River, shown here. Human-caused water shortages can worsen the effects of meteorological droughts.

current risk assessment methodologies.

The Intergovernmental Panel on Climate Change defines compound events as (1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined [*Seneviratne et al.,* 2012].

In some cases, factors are strongly interdependent (e.g., floods at river confluences) and must be treated accordingly in risk assessments. In other cases, there may be some negligible statistical dependency in the system, small enough to assume physical independence (e.g., tide and surge along some coastline stretches). In yet other cases, all variables involved will be truly independent, but the fact that they occur together aggravates their impacts (e.g., tides and river discharge).

As a result, it is important to understand a system's behavior, identify all relevant variables that determine the impacts, and carefully assess whether those variables can be treated as independent or whether more complex dynamical or statistical models need to be used to capture the dependence structure between them.

more than 220,000 recorded fatalities globally. In 2017 alone, major flood disasters in the United States, the Caribbean, and Southeast Asia killed more than 1,000 people, caused damages on the order of hundreds of billions of dollars, and harmed or destroyed the livelihoods of millions of people.

Droughts, a different type of hydrologic extreme, can lead to widespread food and water crises. In the United States, 23 drought and drought-heat wave events between 1980 and 2016 caused economic losses totaling $216 billion. Severe drought conditions in Somalia between 2015 and 2017 have led more than 700,000 people to leave their homes, and these conditions have left more than 6.2 million people in need of humanitarian assistance.

High-impact compound events make up a large portion of these losses, but they are often overlooked in disaster risk analyses and policy agendas. What factors overlap to cause such extremes? And how does one hydrologic extreme lead to other environmental crises? What do we know about them, and what do we still need to know?

Assessing the Risks

Efforts to reduce the risks posed by hydrologic extremes are essential. Accordingly, risk reduction is at the heart of two recent international agreements: the Sendai Framework for Disaster Risk Reduction and the Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts.

However, because compound events emerge from complex processes having multiple causes, they do not conform neatly with traditional categories of extremes or

Synergistic Effects

Although the relationships between flood drivers in coastal areas are well known, current risk assessment techniques mainly consider one driver at a time and ignore the dependence between drivers, leading to underestimation or overestimation of the underlying risk. For example, the dependence between hurricane storm tides, existing groundwater levels, and precipitation is not accounted for in the estimation of the 100-year floodplain by the U.S. Federal Emergency Management Agency used for the National Flood Insurance Program.

Each variable contributing to an extreme compound event is not necessarily an extreme event on its own. For example, a moderate storm surge can cause significant flooding by blocking or slowing typical river discharge or gravity-fed drainage through storm water systems. In the United States, Hurricane Harvey brought intense rainfall to the greater Houston, Texas, area. It also caused a moderate storm surge over 5 days, which reduced the freshwater drainage capacity. Had there not been a storm surge, the flooding would have been less, as the water would have drained faster.

Compounding effects are also apparent when extreme events occur in close succession. One such occurrence hap-

Anthropogenic climate warming is contributing to the increasing size and frequency of wildfires, such as the Thomas Fire, which devastated Southern California in December 2017, seen here. In the western United States, the number of large fires (more than 4 square kilometers) has risen by around 7 fires per year in the past 3 decades.

pened during the 2013–2014 winter storm season in the United Kingdom, when several storms over a short period of time produced large storm surges, high waves, and strong rainfall [*Wadey et al.,* 2014; *Haigh et al.,* 2016]. In such cases, smaller storms that happen after a large storm may have greater impacts than would normally be expected because of factors such as saturated soils, eroded beaches, and weakened flood defenses that leave communities more vulnerable.

When a drought coincides with a heat wave, the impacts are also much greater than when they occur in isolation. The California drought of 2012–2016, for example, is characterized by both below-average precipitation and sustained high temperatures [*AghaKouchak et al.,* 2014]. The precipitation deficits are not the most extreme on record, but record temperatures and multiple extreme heat waves exacerbated the impacts of the hydrological drought.

The Human Dimension

The changing nature of human activities is a challenging aspect of compound events. For example, the availability of freshwater resources in a given location is driven by locally generated runoff as well as discharge from upstream areas. The amount of water coming from upstream is often strongly influenced by human interventions including water withdrawal for irrigation, electricity production, domestic use, and reservoir and land management [*Veldkamp et al.,* 2017; *Mehran et al.,* 2017].

In many regions, water consumption already exceeds the available renewable water supplies, making alternative resources, such as water diversion, desalination, and deep wells, necessary to satisfy the demand.

Not only are anthropogenic influences a feature of most systems, but they can also act to worsen the effects of compound events

The effects of meteorological droughts can be exacerbated by increased human water use. These "anthropogenic droughts" are broadly defined as water stress caused or intensified by such human activities as increased demand, mismanagement, and anthropogenic greenhouse gas emissions [*AghaKouchak et al.,* 2015].

Not only are anthropogenic influences a feature of most systems, but they can also act to worsen the effects of compound events. In Brisbane, Australia, during the 2011 Queensland floods, dam engineers focusing on maintaining an adequate water supply after years of drought failed to anticipate the unusual volume of rainfall that eventually caused the reservoir to overflow the Wivenhoe Dam, causing extensive flood damage downstream [*Van den Honert and McAneney,* 2011]. In a similar context, lack of updated operating rules likely led to the damaging of the Oroville Dam in California in 2017, when an extreme wet season followed a 5-year record-setting drought [*Vahedifard et al.,* 2017].

The Role of Climate Change and Variability

Unraveling the potential influence of climate change and natural variability on compound events is a challenging task because different mechanisms affect the variables involved. Even if the driving variables are stationary, their dependence structure may change, which changes the likelihood that they will coincide.

Recent research has already revealed changes in the frequency of the concurrence of storm surges and rainfall [*Wahl et al.*, 2015] and drought and heat waves [*Mazdiyasni and AghaKouchak,* 2015] in the United States. Given the expected rise in global temperatures due to human activities, the chance

A forest regrows in Grand Canyon National Park after a massive wildfire. Though fires devastate the landscape, they also enrich the soil with nutrients from decomposed organic matter. The regrown forest can look very different from the original one, leading to a different ecosystem and biodiversity.

of concurrent droughts and high temperatures will likely increase in the future. Higher sea levels will likewise increase the chance of compound flooding in coastal regions [*Moftakhari et al.,* 2017].

Although the popular press sometimes attributes extreme weather events to climate change, establishing the most likely causes of a given event is an emerging field and particularly challenging for compound events. A recent report by the *National Academies of Sciences, Engineering, and Medicine* [2016] takes an important step toward benchmarking scientific approaches that characterize uncertainty and articulation of event attribution. However, compound events quickly illuminate the challenge of understanding and attributing interlinked phenomena. The propagation of errors and uncertainties inherent in creating models of these phenomena potentially imposes limits on usable knowledge for climate adaptation concerns.

The Way Forward

Experts who study and simulate extreme events and their impacts are best able to pinpoint knowledge gaps. In this vein, future efforts to address hydrologic compound events will benefit from efforts on several fronts.

System stress tests can be exploited to articulate the relevant attributes of the impact system [e.g., *Bevacqua et al.,* 2017]. These approaches include understanding how human (ir)rational behavior may trigger, create, or alleviate the occurrence and impact of compound events.

Additional key variables and event combinations that require further analysis must be identified [e.g., *Liu et al.,* 2016]. Appropriate statistical methods must be used to simulate dependence in time and space [*Haigh et al.,* 2016] and across multiple variables [e.g., *Wahl et al.,* 2015]. Data and model requirements must be identified for documenting, understanding, simulating, and attributing compound events. Last, compound events must be incorporated into impact assessments and disaster risk mitigation works [e.g., *Zheng et al.,* 2017].

These efforts will be enhanced by close collaboration and communication between scientists from various fields, including natural sciences, engineering, and social sciences, as well as stakeholders and policy makers. Research in this area is still in its infancy. A community effort, including promotion by major scientific associations, will help improve methods of detection, modeling,

Research in this area is still in its infancy.

and risk assessment of compound extremes. For example, the recently established European Union COST Action Network on "Understanding and modeling compound climate and weather events (DAMOCLES)" will facilitate international collaboration on this important topic.

References

AghaKouchak, A., et al. (2014), Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought, *Geophys. Res. Lett., 41,* 8,847–8,852, https://doi.org/10.1002/2014GL062308.

AghaKouchak, A., et al. (2015), Water and climate: Recognize anthropogenic drought, *Nature, 524,* 409–411, https://doi.org/10.1038/524409a.

Bevacqua, E., et al. (2017), Multivariate statistical modelling of compound events via pair-copula constructions: Analysis of floods in Ravenna, *Hydrol. Earth Syst. Sci., 21,* 2,701–2,723, https://doi.org/10.5194/hess-2016-652.

Haigh, I. D., et al. (2016), Spatial footprint and temporal clustering analysis of extreme sea level and storm surge events around the coastline of the UK, *Sci. Data, 3,* 160107, https://doi.org/10.1038/sdata.2016.107.

Liu, B., Y. L. Siu, and G. Mitchell (2016), Hazard interaction analysis for multi-hazard risk assessment: A systematic classification based on hazard-forming environment, *Nat. Hazards Earth Syst. Sci., 16,* 629–642, https://doi.org/10.5194/nhess-16-629-2016.

Mazdiyasni, O., and A. AghaKouchak (2015), Substantial increase in concurrent droughts and heatwaves in the United States, *Proc. Natl. Acad. Sci. U. S. A., 112,* 11,484–11,489, https://doi.org/10.1073/pnas.1422945112.

Mehran, A., et al. (2017), Compounding impacts of human-induced water stress and climate change on water availability, *Sci. Rep., 7*(1), 6282, https://doi.org/10.1038/s41598-017-06765-0.

Moftakhari, H. R., et al. (2017), Compounding effects of sea level rise and fluvial flooding, *Proc. Natl. Acad. Sci. U. S. A., 114,* 9,785–9,790, https://doi.org/10.1073/pnas.1620325114.

National Academies of Sciences, Engineering, and Medicine (2016), *Attribution of Extreme Weather Events in the Context of Climate Change,* Natl. Acad. Press, Washington, D.C., https://doi.org/10.17226/21852.

Seneviratne, S., et al. (2012), Changes in climate extremes and their impacts on the natural physical environment, in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change,* edited by C. B. Field et al., pp. 109–230, Cambridge University Press, Cambridge, U.K., https://doi.org/10.1017/CBO9781139177245.006.

Vahedifard, F., et al. (2017), Lessons from the Oroville Dam, *Science, 355*(6330), 1,139–1,140, https://doi.org/10.1126/science.aan0171.

Van den Honert, R. C., and J. McAneney (2011), The 2011 Brisbane floods: Causes, impacts and implications, *Water, 3,* 1,149–1,173, https://doi.org/10.3390/w3041149.

Veldkamp, T. I. E., et al. (2017), Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century, *Nat. Commun., 8,* 15697, https://doi.org/10.1038/ncomms15697.

Wadey, M. P., I. D. Haigh, and J. M. Brown (2014), A century of sea level data and the UK's 2013/14 storm surges: An assessment of extremes and clustering using the Newlyn tide gauge record, *Ocean Sci., 10,* 1,031–1,045, https://doi.org/10.5194/os-10-1031-2014.

Wahl, T., et al. (2015), Increasing risk of compound flooding from storm surge and rainfall for major US cities, *Nat. Clim. Change, 5,* 1,093–1,097, https://doi.org/10.1038/nclimate2736.

Zheng, F., M. Leonard, and S. Westra (2017), Application of the design variable method to estimate coastal flood risk, J. Flood Risk Manage., 10, 522–534, https://doi.org/10.1111/jfr3.12180.

Zscheischler, J., et al. (2018), Future climate risk from compound events, *Nat. Clim. Change, 8,* 469–477, https://doi.org/10.1038/s41558-018-0156-3.

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MODELING THE
MELTING PERMAFROST

By Irina Overeem, Elchin Jafarov, Kang Wang, Kevin Schaefer, Scott Stewart, Gary Clow, Mark Piper, and Yasin Elshorbany

Melting permafrost slumps down an Arctic coast slope. Credit: National Geographic Image Collection/Alamy Stock Photo

A new resource makes it easier for researchers to explore how melting permafrost might affect carbon release, wetlands, and river deltas.

Climate change is causing vast expanses of permafrost to thaw. Scientists are busy quantifying how future thawing could expose massive, previously frozen pools of carbon and trace elements, releasing them to the global biogeochemical cycles [*Schuur et al.*, 2015; *Schuster et al.*, 2018]. But the ways in which permafrost thaw is interwoven with hydrological and geomorphological processes and how carbon and toxic heavy metals spread throughout the thawing Arctic are sweeping, yet unanswered, research questions.

Permafrost—ground that stays at or below 0°C for 2 or more years—can be found under 24% of the

This aerial photo taken over Alaska shows one of the ways in which thawing permafrost reshapes the landscape. Credit: iStock.com/GeorgeBurba

Northern Hemisphere's land surface [*Zhang et al.*, 1999]. The frozen subsurface profoundly influences the hydrological cycle of the Arctic region.

For example, the thawing ground below creates unique geomorphic patterns: drooling solifluction lobes that form when wet soil oozes downhill, giraffe skin polygons formed by ice wedges filling the cracks in freeze-shrunken soil, thaw lakes and seasonal wetlands, and melting coastal bluffs.

Permafrost thaw contributes to the global hydrological and carbon cycles, and it also has a significant impact on roads, housing, and coastal infrastructure. This impact is predicted to create a multibillion-dollar infrastructure maintenance problem for Alaska over the span of the 21st century [*Melvin et al.*, 2017].

Evaluating current and future permafrost conditions requires numerical modeling, but the time and effort required to develop or run such models remain a barrier to their use. To address this issue, we have developed online, easily accessible permafrost process models for use by scientists and educators through the Community Surface Dynamics Modeling System (CSDMS) at the University of Colorado. We call this product the Permafrost Modeling Toolbox.

An Easy-to-Use Interface

CSDMS provides a Web-based modeling environment consisting of selected open-source numerical models of permafrost dynamics and other surface processes. Our projects, which use the CSDMS cyberinfrastructure specifically for permafrost research, are funded by the National Science Foundation Office of Polar Programs, NASA, and the U.S. Department of Energy.

Our toolbox of coupled permafrost and Earth surface models is designed to be modular to meet the needs of a variety of users: students learning about thermal processes, industry scientists who need to make an initial environmental assessment, and members of the academic community interested in system feedbacks (Figure 1).

We use a Web-based modeling tool (WMT) that allows users to quickly select a model and configure its inputs and then run it remotely. Leveraging CSDMS standards and software infrastructure allows users to quickly document metadata with the models, share code through a version-controlled repository on the online hosting service GitHub, and distribute educational material through hands-on modeling labs.

A Flexible Design

The toolbox currently includes three permafrost models of increasing complexity, all driven by local climate forcing, to meet a variety of needs:

- An empirical model, the Air Frost Number model [*Nelson and Outcalt*, 1987] predicts the likelihood of permafrost occurring at a given location.
- An analytical-empirical model, the Kudryavtsev model [*Anisimov et al.*, 1997] provides an exact solution to thermodynamic equations accounting for snow, vegetation, and soil to calculate active layer thickness (the average annual thaw depth).
- A numerical heat flow model, the Geophysical Institute Permafrost Lab (GIPL) model [*Jafarov et al.*, 2012] includes the latent heat effects in the active layer zone. This model divides a vertical profile into multiple layers of soil and substrate with different thermal properties, and it calculates temperature profiles with depth.

Repeated freezing and thawing of subsurface permafrost has buckled this road in Canada's Northwest Territories. Thawing permafrost is expected to do significant damage to roads and other infrastructure in the coming decades. Credit: iStock.com/RyersonClark

The first two models are developed as "components" that can be coupled to other CSDMS models. The GIPL model functions as a stand-alone code, and it will be fully embedded into the CSDMS model coupling framework at a later date. All three models are inherently one-dimensional; that is, they calculate the thermal state over time for a single vertical column, but they do not calculate heat exchange among columns. However, each model can run regional simulations or even be implemented for the entire Arctic region.

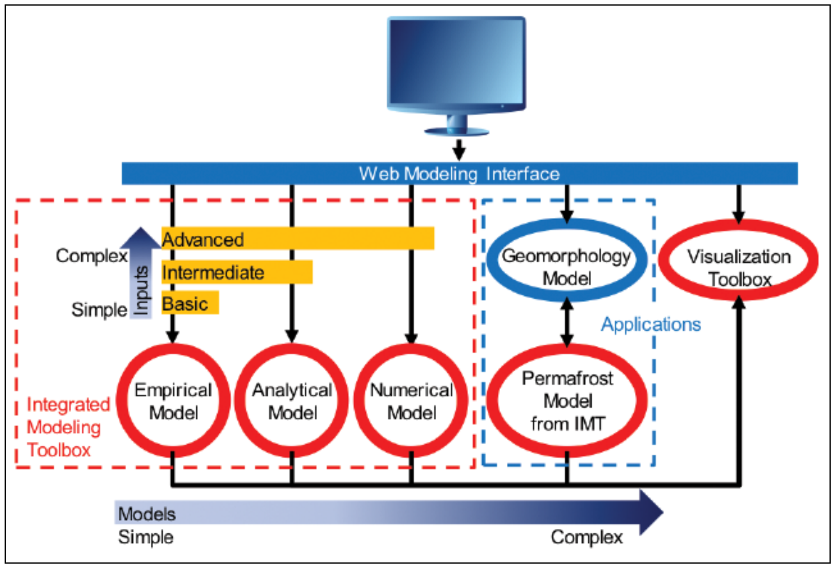

Fig. 1. The Permafrost Modeling Toolbox contains models with varying degrees of complexity that can be coupled to preprocessed data sets. The models can also be coupled with hydrological, geomorphological, or other types of models.

Straightforward Data–Model Coupling

Our project pairs these models with preassembled data sets of input parameters. Casual model users can then quickly run experiments for selected time series and given regions. Data sets include long-term climatological and permafrost observations in coastal and interior Alaska (Barrow and Fairbanks, respectively), as measured at Circumpolar Active Layer Monitoring Network (CALM) and U.S. Geological Survey stations [*Urban and Clow*, 2017].

Access to data and models together allows users to compare model output with in situ observations directly. In addition, a regional climatological data set comprising observed monthly temperature and precipitation data for the 20th century is available to drive the models for Alaska. To explore future trends in permafrost, another data set comprises parameters of the Coupled Model Intercomparison Project Phase 5 (CMIP5) modeled climate data until 2100 [*Taylor et al.*, 2012], specifically applied to the known permafrost zone.

We realize that additional data sets will need to be brought in to facilitate new discoveries, but we offer the preprocessed data sets so that users can test a hypothesis quickly before embarking on a more detailed coupling of models with data. Moreover, the data sets and models are set up with common interfaces, so puzzle pieces can be put together in different combinations with relative ease.

Applications of the permafrost toolbox include calculating permafrost for real-world sites in the Arctic region, looking at warming trends over the past century, making maps of future permafrost, and comparing models with different complexities.

Figure 2 shows one such example: Calculations of the current and future active layer thickness over the entire

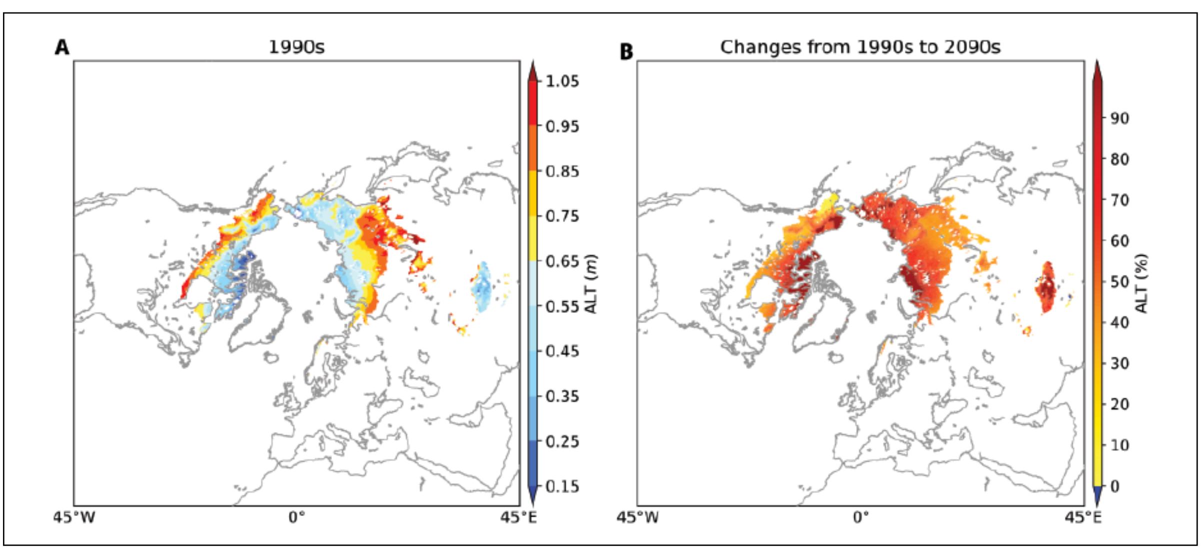

Fig. 2. Calculation of the recent state of permafrost and a projection of changes by the end of the 21st century. (a) This map of the permafrost active layer thickness (ALT)—the average annual thaw depth—over the entire Northern Hemisphere was calculated with climate data from the 1990s. (b) This map of the relative deepening in permafrost active layer thickness was calculated with CMIP5 climate model output for the 2090s.

The waterlogged permafrost landscape of the North Slope of Alaska demonstrates the importance of feedback linkages between permafrost thaw, the hydrological system, and river transport, but these feedbacks have not yet been quantified in predictive models of permafrost. Credit: Irina Overeem

More advanced modelers interested in permafrost and Earth surface processes will find detailed information on our online collaborative platform on GitHub (bit.ly/Git-Hub). This platform also provides a means for advanced modelers to comment, suggest improvements, download code, or contribute new codes.

We anticipate that this resource will bring together researchers with various levels of modeling and field expertise to find answers to long-standing questions about permafrost and its link to surface processes and to formulate predictions about how these processes will evolve.

Arctic region demonstrate a considerable deepening of this critical seasonal layer. This experiment is relatively straightforward to perform using the Web-based modeling tool.

We have developed educational material to help users learn about these tools or, more generally, to learn about the physical processes of permafrost dynamics. Four hands-on modeling labs are available for new users. This material is accessible for teaching use, and the online labs include instructions for classroom use and undergraduate lesson plans.

Coupled Permafrost and Earth Surface Process Modeling

More challenging problems involve assembling models that couple the new components with other Earth surface process models. The design of models in our toolbox includes a basic model interface that allows information to be passed easily between different models. This capability could be applied, for example, to feedbacks between geomorphic processes and sequestering of carbon. These coupled processes are still largely unexplored, but they have been shown to be potentially significant in topographically complex terrain [*Shelef et al.,* 2017].

Currently, we are using this capability to investigate the unique evolution of river deltas in permafrost terrain. Modeling of the intrinsic controls of permafrost on Arctic deltas highlights the role of the cohesiveness of frozen sediment and shows less dense, more stable distributary deltaic networks than in typical lower-latitude settings. Such effects on deposition in delta networks may importantly affect the role of these deltas as hot spots of carbon storage.

Other possible couplings are between landscape evolution models, hydrological models, and the new permafrost models. Such entirely new integrated models require a higher level of programming expertise and scientific creativity to generate hypotheses and identify the physical processes to be coupled in each of the process domains. The software framework of CSDMS can expedite such modeling endeavors.

Acknowledgments

This work was funded by grant NSF-OPP 1503559 and the Next-Generation Ecosystem Experiments Arctic project, DOE Office of Science.

References

Anisimov, O. A., N. J. Shiklomanov, and F. E. Nelson (1997), Global warming and active-layer thickness: Results from transient general circulation models, *Global Planet. Change, 15*(3–4), 61–77, https://doi.org/10.1016/S0921-8181(97)00009-X.

Jafarov, E. E., S. S. Marchenko, and V. E. Romanovsky (2012), Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset, *Cryosphere, 6*(3), 613–624, https://doi.org/10.5194/tc-6-613-2012.

Melvin, A. M., et al. (2017), Climate change damages to Alaska public infrastructure and the economics of proactive adaptation, *Proc. Natl. Acad. Sci. U. S. A., 114*(2), E122–E131, https://doi.org/10.1073/pnas.1611056113.

Nelson, F. E., and S. I. Outcalt (1987), A computational method for prediction and regionalization of permafrost, *Arct. Alpine Res., 19*(3), 279–288, doi:10.1657/1523-0430(07-069).

Schuster, P. F., et al. (2018), Permafrost stores a globally significant amount of mercury, *Geophys. Res. Lett., 45*(3), 1,463–1,471, https://doi.org/10.1002/2017GL075571.

Schuur, E. A. G., et al. (2015), Climate change and the permafrost carbon feedback, *Nature, 520*(7546), 171–179, https://doi.org/10.1038/nature14338.

Shelef, E., et al. (2017), Large uncertainty in permafrost carbon stocks due to hillslope soil deposits, *Geophys. Res. Lett., 44*(12), 6,134–6,144, https://doi.org/10.1002/2017GL073823.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc., 93*(4), 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1.

Urban, F. E., and G. D. Clow (2017), DOI/GTN-P climate and active-layer data acquired in the National Petroleum Reserve–Alaska and the Arctic National Wildlife Refuge, 1998–2015, *Rep. 1021,* 558 pp., U.S. Geol. Surv., Reston, Va., https://doi.org/10.3133/ds1021.

Zhang, T., et al. (1999), Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere, *Polar Geogr., 23*(2), 132–154, https://doi.org/10.1080/10889379909377670.

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Thriving Earth Exchange: Five Years of Community-Driven Science

AGU launched Thriving Earth Exchange as part of a Centennial commitment to leverage our science to benefit humanity.

Over the past 5 years, Thriving Earth Exchange has launched more than 80 projects that have three things in common: They use Earth and space science, they make a concrete local impact, and most important, the projects are community driven. Thriving Earth Exchange empowers communities to decide what they want to accomplish and fosters scientific partnerships to help them accomplish their goals.

AGU launched Thriving Earth Exchange as part of a Centennial commitment to leverage our science to benefit humanity; however, we've found that this community-driven approach yields real benefits for our science and for scientists as well. Thriving Earth Exchange introduces previously unexplored questions and techniques to our fields. It creates new partnerships and opportunities for AGU and helps our scientists learn novel skills and expand their careers. It helps diversify science through workshops and projects that are led by women and people of color. Thriving Earth Exchange even contributes to public support for investment in science. Eboni Cochran, a community leader who is working with Thriving Earth Exchange to improve air quality in the "Rubbertown" neighborhoods of Louisville, Ky., wrote a letter of support that was read on the floor of the U.S. Senate during the 2017 budget debate.

Although all projects are driven by community priorities, three main themes have emerged: reducing the impact of natural hazards, cleaning up pollution, and addressing climate change.

Reducing Natural Hazard Impacts

As the number and severity of natural disasters grow, more projects are working to prevent hazards, particularly flooding. As part of AGU's Fall Meeting 2017 in New Orleans, La., Thriving Earth Exchange cohosted a tour of the city, that included a visit to one of the city's new rain gardens. These rain gardens are part of a citywide effort to store water until it can flow naturally out of the city, rather than flooding adjacent neighborhoods. This nature-based approach to resilience is a common feature of many Thriving Earth Exchange projects.

In the Chantilly neighborhood of New Orleans, Thriving Earth Exchange worked with ISeeChange, a locally led citizen science project, to help collect and analyze data and

A neighborhood rain garden capable of retaining 88,000 gallons (about 333,000 liters) of water on Wildair Drive in New Orleans, La., completed by the New Orleans Redevelopment Authority. The orange bench and signage at this and other sites help residents and visitors identify and learn about these innovative approaches to water management. Credit: New Orleans Redevelopment Authority stories about neighborhood flooding. Scientists at the National Weather Service used those data to improve local hydrological forecasts, and Chantilly residents used them to convince the city to enlarge the footprint of a proposed resilience effort to include their neighborhood.

Approximately 1,125 kilometers east, Thriving Earth Exchange helped design a green and flood-resilient city hall in Midway, Ga. The new city hall was the initiative of the mayor, who rallied her city around beautification, efficiency, and improved city services. Students from nearby Savannah State University, working with Thriving Earth Exchange scientists, added ditches to collect rainwater, permeable paving, rain gardens, and cisterns to the city hall site plan. The results included lower operating costs and reduced flood risk and ensured accessibility during extreme rain events. Upon reviewing the high-quality student work, a local engineering firm certified the drawings for free.

This project highlights the importance of beginning with community priorities. Local climate adaptation was enabled by the mayor's commitment to safety and reliability and her willingness to explore new strategies to meet those goals.

Cleaning Up Pollution

One of the earliest Thriving Earth Exchange projects tackled air pollution in the northeastern corner of Denver, Colo. Residents were concerned about spilled chemicals from long-abandoned dry cleaning operations that may have been transported by groundwater and were releasing gases into the basements of local homes. Although the scientific leads on the project designed a testing and mapping program, community leaders insisted that the project offer individual residents options for remediation, something the scientists hadn't focused on. The most efficient remediation option was to ventilate the basement or crawl space in the same way these spaces are ventilated for radon. By combining the testing for dry cleaning chemicals with testing for radon, homeowners became eligible for a program that helped fund radon remediation.

> This nature-based approach to resilience is a common feature of many Thriving Earth Exchange projects.

Not only did this eligibility help individual residents respond when tests revealed the presence of dangerous gases, but also it led to a better understanding of radon as an environmental justice issue in Denver and the surrounding area. Radon is ubiquitous in Denver, and it is more likely to affect renters, older homeowners who bought their home before radon testing was routine, and low-income residents who cannot afford remediation. As a result of this project, a coalition of scientists and community and business leaders has launched an ambitious program of radon awareness and testing. In their first 6 months they have distributed radon testing kits, hosted 12 community events, and helped 42 homeowners.

One of the key lessons for this project is the importance of focusing on concrete outcomes. The map of the distribution of chemicals and its connection to remediation is what made the project effective. Thriving Earth Exchange works to focus projects toward action, not just understanding.

Addressing Climate Change

Thriving Earth Exchange is working with communities in the Pamir Mountains, which span the border between Afghanistan and Tajikistan, to recover traditional ecological calendars. These calendars were used for centuries to track local conditions, as well as ecological patterns, to adjust agricultural and pastoral practices. Historically, these calendars were constantly refined and updated on the basis of experience, but they haven't been used for decades. In some places, the calendars were actively suppressed in favor of larger-scale agricultural planning. Decades of military activity, often by outsiders, have also thwarted traditional agriculture practices.

After recovering the calendars, local communities found them to be out of sync with the environment. The rapidly changing climate, especially in mountainous regions, meant that the cues for planting, harvesting, and pastoral activities no longer matched local conditions. Village leaders are working with climate scientists to update these calendars and then use them to develop climate-resilient agricultural and pastoral practices. Trees and bushes planted and cared for using these updated calendars bore their first fruit last year.

This project highlights the importance of intellectual humility in community-driven projects. Rather than insist that villagers adopt international climate forecasts based on Western calendars, scientists on the project opted to respectfully contribute observations and data to a far older tradition.

What's Next

Thriving Earth Exchange envisions a day when community collaboration is as much a part of the toolbox of geoscience as numerical modeling, fieldwork, and long-term monitoring. To accomplish this, Thriving Earth Exchange and AGU have four goals: increase the number of community science projects, including expanding our international efforts; create more varied ways for scientists and community leaders to be part of community science projects; advance community science as a scholarly enterprise; and increase recognition for community science.

Visit the Thriving Earth Exchange website, thrivingearthexchange.org, to explore community science opportunities, get involved, and share your stories.

By **Raj Pandya** (rpandya@agu.org), Director, Thriving Earth Exchange, AGU

Lifting Up the Next Generation: The Austin Grant Challenge

Thousands of students attend AGU's Fall Meeting to present their work at poster sessions, meet potential mentors in their field, and seek out new career opportunities. Credit: Event Photography of North America Corporation

Spring promises new beginnings and opportunities for personal and professional growth. And 2019 is also AGU's Centennial year—a time for our community to celebrate the scientific advances made in Earth and space science over the past 100 years. For me, the Centennial leads me to consider how we can make sure that our science will prosper and contribute to society for the next century.

I believe that to flourish in the years ahead, we must take steps now to expand AGU's membership, transcend our traditional demographics and cultural boundaries, and create a more diverse and global community. We must support young scientists who are eager to join our ranks and help them to overcome whatever may stand in their way. These young men and women have the potential to become the next generation of leaders in Earth and space science. They will bring innovative ideas and cultural perspectives. They will bring a surge of new energy and scientific expertise to face the great issues of tomorrow—something science and society needs. But only if we are able to open the door for them.

It is imperative that members of AGU commit to developing this next generation by making a personal pledge to invest in and support them. That is why I am asking you to join me in donating to the Austin Endowment for Student Travel Grant Challenge.

We must support young scientists and help them to overcome whatever may stand in their way.

Rising to the Challenge

Last October, scientist and AGU Development Board member Jamie Austin issued a challenge to the AGU Earth and space science community. Recognizing the life-changing potential of Fall Meeting, Dr. Austin generously offered to match all donations to the Austin Endowment for Student Travel to AGU's Fall Meeting up to the amount of $1 million.

Fall Meeting is much more than a science meeting. It is the largest annual gathering of international Earth and space scientists in the world, where researchers who span generations and scientific disciplines join together to advance the scientific enterprise. It is a place where a young scientist can hear about the latest work of leading researchers in their field and also present their own work—some for the first time—to their peers. It is a place where lifelong professional connections and relationships, some of which influence their professional careers, are built and strengthened. It is a place where ideas are exchanged that spark new research and where those who want to explore science communications learn about science policy advocacy. It is a place to discover career opportunities and find support. Virtually nowhere else can a young scientist—or, for that matter, a scientist of any age or career stage—experience all of these opportunities in one place.

However, for young scientists who are still in school or freshly graduated and likely saddled with student debt and/or without a good income, the expense of traveling to and registering for Fall Meeting can be prohibitive. As a result, many miss out—and we miss out.

No doubt there are many worthy organizations and causes that you may be considering for your donations. I ask that you consider the current landscape of the funding for the Earth and space sciences in making your decision about where to give. Historically, science has been viewed through an apolitical lens and has been valued for its global, far-reaching contributions that benefit humanity. Of late, however, the environment for scientific funding has grown less hospitable, less generous. As this gap in funding has grown even larger, the impacts are particularly far-reaching for young scientists who are at the precipice of entering or remaining in the field of Earth and space sciences.

From Member to Philanthropist

Finally, I wish to make a distinction between membership and philanthropy. By donating to the Austin Endowment for Student Travel, you transform from a passive transactional state—a member who attends meetings, reads or perhaps contributes to journals or *Eos*—to an active state: a philanthropist who is shaping the very future of our field for years to come. You can play an essential role in ensuring the future of our dynamic community.

With your support, we have the opportunity to create a fund of $2 million to support students attending AGU Fall Meetings for years to come. Think of all the good your donation can do. I hope you will join me in meeting this challenge to ensure that those on whom we will rely to contribute to the next century of discovery are poised to join our community.

Donate today at giving.agu.org.

By **Carlos A. Dengo** (development@agu.org), Chairman, Development Board, AGU

Grassroots Engagement Grants Support Centennial Activities

As part of our Centennial celebration, AGU launched an exciting new grant program: the Celebrate 100 Grants.

With the start of 2019, AGU's Centennial is now in full swing. And what better way to celebrate than by having you, our members, create and plan events across the globe? Our goal for AGU's Centennial is to enable our members and partners to share the wonder and excitement of Earth and space science and how scientific research and discovery benefits communities and society. There are several exciting ways for you to do this, all of which are designed to help you either reflect on Earth and space science's past or help inspire the next century of discovery—or both.

One of the ways you can take an active role in the Centennial celebration is through the Celebrate 100 Grants program, which enables our members and partners to share the wonder and excitement of Earth and space science with the broader community and the public. These grants, which are open to members and non-members, are a cornerstone of AGU's Centennial. They "support projects demonstrating innovation, collaboration, impact and sustainability in promoting the value of Earth and space science, primarily to the public." The winners announced thus far include individuals and groups who collectively exemplify the power and global value of our science. Their work should serve as an inspirational example for others looking for ways to engage in AGU's Centennial.

Supporting a Community-Driven Celebration

The Centennial is a celebration of 100 years of the Earth and space science AGU represents and the dedicated, groundbreaking scientists who have made the past 100 years of discoveries, innovations, and solutions possible. Our history is a rich, complex, and important story, and paying tribute to that history—particularly to the diversity of the sciences we represent—is a critical part of understanding the possibilities of future scientific efforts.

AGU's Centennial is the start of the next transformational era of Earth and space science, and using the energy of those past achievements will help us to bring public attention to the value of our work and to accelerate the advancement of science. Who better to lead that celebration than you, the leaders and voices of our science? With this grant program we are striving to support the amazing ideas that we know you have for transforming our science, building bridges between our community and those we serve, and inspiring the world with the power Earth and space science has to benefit humanity.

Setting the Stage for the Next 100 Years

AGU is offering grants for activities with the goal of

- Increasing awareness of the importance and impact of Earth and space science issues
- Increasing the recognition of AGU among decision makers as an authoritative source of integrated, interdisciplinary Earth and space science information
- Increasing the effectiveness of Earth and space scientists to communicate the value and resonance of their work in informing science policy
- Enhancing engagement and involvement of students and early-career scientists
- Enhancing mutual support and networking opportunities for scientists
- Developing strategies for collaboration with other societies and partners

How will you transform our science, build bridges between our community and those we serve, and inspire the world with the power Earth and space science has to benefit humanity?

How to Write a Successful Grant Proposal

We are accepting grant applications on a rolling basis through approximately the end of 2019. Grants will be awarded at two levels: (1) microgrants, which are up to $1,000, and (2) major grants, which are between $1,001 and $10,000. Grants are not limited to AGU members, and institutions are encouraged to apply.

We are looking for the following types of characteristics in proposed events:

- Demonstrating innovative ways to communicate or celebrate science
- Showing the impacts of Earth and space science
- Collaborating with principals from multiple organizations or partners
- Showing the progression of science and being future or forward thinking

On 19 January 2019, girls from local government schools in the small sub-Saharan country of Malawi gather for the first of four Girls Science Day clinics, led by Celebrate 100 Grant awardee Rochelle Holm and her team at Mzuzu University. Credit: Rochelle Holm

- Showing impact and, potentially, lasting impact either on a targeted group or on a larger community
- Reaching beyond a local community
- Showing capacity to grow transformative new techniques, develop new methodologies, or build new networks

In addition to supplying the grant funding, AGU will offer expert advice and support throughout the planning and execution of your event, as well as help to enable you to use AGU's extensive networks to promote your event/activity. Examples of potential events or activities might include launching a crowdsourced data rescue project, creating a mentoring program for graduate students, hosting an outreach program at your local middle school, creating an app that can convey Earth and space science and capture people's attention, or buying a stall at a local farmer's market for a season to have an "Ask the Scientist" stand.

As the Centennial progresses, we will be sharing information about all the events planned on the Centennial website, as well as in *Eos*, AGUniverse, and From the Prow, and on AGU's social media channels. There's still plenty of time for you to apply for a Celebrate 100 Grant. Get inspired by our map at bit.ly/100-around-the-globe showing where our community is celebrating the discovery-to-solutions journey of the past 100 years and the next 100 years of Earth and space science!

Apply for an AGU Celebrate 100 Grant now at bit.ly/100_Grants.

By **Chris McEntee** (agu_execdirector@agu.org), Executive Director/CEO, AGU

How Monsoons in Africa Drove Glacier Growth in Europe

EOS CENTENNIAL COLLECTION

Aletsch Glacier in Switzerland. Credit: iStock.com/Simon Dannhauer

Around 250,000 years ago, most of North America and northern Europe was covered in glaciers. These massive ice sheets formed over thousands of years and waxed and waned in response to a long list of factors, including wobbles in Earth's orbit, alterations in the atmosphere, and changing ocean currents. Now scientists have added another mechanism to that list: distant monsoons.

Continental ice sheets are supposed to remain fairly stable during an ice age, but that is not always the case. During a frigid period of the late Quaternary, large chunks of the European ice sheet melted and refroze, temporarily creating large, warm pools of meltwater in the Bay of Biscay, the gulf between Spain and France.

Recent studies have shown that distant, low-latitude weather events such as the East Asian monsoon can affect glaciers far away, at much higher latitudes. To test whether monsoons could explain the European ice sheet's ebb and flow, *Kaboth-Bahr et al.* examined cores of sediment extracted from the deep seafloor near the Strait of Gibraltar, as well as cores from two other locations. Using the ratio of light to heavy minerals in the sediment as a proxy for the volume and force of water flow at the seafloor, they reconstructed ancient ocean currents dating back 250,000 years.

The sediment revealed that when monsoons periodically weakened in northeastern Africa, thus drying up the Nile River, the change caused saltier water to rush out of the Mediterranean Sea through the Strait of Gibraltar and into the Atlantic. As this relatively warm, salty water hit the Atlantic, it produced what is known as the Azores Current, a branch of the Gulf Stream that drags warm Atlantic waters toward England and northern Europe. During glacial periods, the pooling of this warm Atlantic water generates the moisture that makes ice sheets grow.

This monsoon-driven current helps to explain the European ice sheet's periodic growth, the team suggests. It could also help scientists understand how monsoons are affecting Earth's glaciers today. (*Geophysical Research Letters*, https://doi.org/10.1029/2018GL078751, 2018) **—Emily Underwood, Freelance Writer**

Improving Air Quality Could Prevent Thousands of Deaths in India

More than 6.1 million people worldwide die each year as a result of exposure to air pollution, which increases the risk of cardiovascular disease, lung disease, and cancer. In India, which contains many of the world's most polluted cities, the annual death toll from air pollution exceeds 1.6 million. A new study shows how implementing stricter emissions standards in India could save hundreds of thousands of lives each year.

One of the most dangerous components of air pollution is fine particulate matter ($PM_{2.5}$), nanoscopic particles and droplets produced by burning fuels, which travel deep into the lungs and bloodstream and damage the lungs and heart. On average, Indian citizens are exposed to $PM_{2.5}$ concentrations between 15 and 32 times the air quality guidelines set forth by the World Health Organization, and scientists project that India's $PM_{2.5}$ levels will double by 2050 relative to 2015. In New Delhi, one of the world's most polluted megacities, $PM_{2.5}$ concentrations have reached more than 1,200 micrograms per cubic meter, 48 times the guideline established by the World Health Organization.

Morning smog in New Delhi, India. Credit: iStock.com/BDphoto

The Indian government has policies in place to reduce the rapid rise of pollution, such as curbing emissions from buses and trucks and expanding the household use of liquified petroleum gas to replace solid fuels. In their new study, *Conibear et al.* decided to compare India's existing and planned policies to a more aggressive plan to reduce emissions. They used a high-resolution computer model to estimate the pollution levels people breathe at ground level throughout India and test how different emissions policies would affect their exposure and health.

Under India's existing and planned policies, dubbed the New Policy Scenario, the rate of growth in Indian citizens' exposure to pollution decreased by 9%, the authors found. Compared to the present day, that plan of action will avert about 61,000 premature deaths in 2040, they calculated. A more aggressive plan, called the Clean Air Scenario, will decrease the rate of growth in air pollution by about 65% and avert around 610,000 deaths, they found.

Even with zero emissions growth, India's rapidly growing and aging population means that the rates of disease and premature mortality caused by air pollution will increase by 75% from 2015 to 2040. Despite that grim statistic, the team argues, hundreds of thousands of deaths could be avoided through tighter emissions standards—like cleaner iron and steel manufacturing—and universal access to clean household energy. (*GeoHealth*, https://doi.org/10.1029/2018GH000139, 2018)
—Emily Underwood, Freelance Writer

Wind Speed Governs Turbulence in Atmospheric Inversions

On clear, calm nights, the cooling of Earth's surface creates a unique layer of air between 10 and 100 meters above the ground in which the temperature increases with height. Because the presence of warmer air overlying denser, cooler air is thermally very stable, these inversions, which are also called stable boundary layers (SBLs), suppress turbulence and vertical mixing. This can result in adverse effects, including the buildup of high concentrations of pollutants near the ground that may affect air quality and human health.

Although previous studies have demonstrated that SBLs can be either weakly or strongly stratified, the mechanisms responsible for these variations are not well understood. To determine how turbulence varies under different conditions, *Lan et al.* conducted a field campaign at the Idaho National Laboratory. They measured the wind field in three dimensions—as well as temperature, water vapor density, and other atmospheric conditions—using four eddy covariance systems mounted at heights of 2, 8, 16, and 60 meters on a tower over flat terrain.

The results indicated that the speed of winds measured a couple of meters above the ground determines the structure of a swirling type of turbulence known as an eddy. When these near-surface winds are weak, the eddies are confined to a thin layer of air, which suppresses vertical mixing and reduces the downward transport of heat. These changes ultimately lead to a more strongly layered inversion. By contrast, when stronger winds are present near Earth's surface, larger-scale eddies can form. These enhance vertical mixing, which weakens the stratification and allows even larger eddies to develop.

These findings suggest that SBLs can be classified according to average near-surface wind speeds. By showing that the structure of turbulence varies significantly between weakly and strongly stratified inversions, the authors provide important insights into the differences between these end-member states and how turbulence within SBLs should be characterized in both climate and weather models. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2018JD028628, 2018) **—Terri Cook, Freelance Writer**

A New Tool for Studying Volcanic Eruptions Like Kīlauea

Lava flows from Kīlauea during an eruption in May 2018. Credit: USGS/Handout/Anadolu Agency/Getty Images

On 3 May 2018, lava burst through the foot of Kīlauea, Hawaii's most active volcano. The eruption continued for months, consuming hundreds of homes as molten rock flowed downhill into the Pacific Ocean. A new study characterizes how such events—known as effusive eruptions—erode the volcanic conduit through which magma flows over time. This finding could help scientists better understand how Kīlauea and similar volcanoes wreak havoc.

Unlike violent, explosive eruptions like the 1980 Mount St. Helens event, effusive eruptions occur when lava simply pours or flows out of fissures and cracks around a volcano. To predict how long an effusive eruption like Kīlauea's will last and how far the lava will travel, scientists need to know the effusion rate, or the rate at which hot, molten rock is flowing out. Many variables affect this rate, including how fast the magma reservoir below empties and refills and the properties of the rock through which the magma moves. The rate of magma refill can also affect how fast volcanic conduits erode, a factor that few studies have examined before.

To address this knowledge gap, *Aravena et al.* created a computer model that simulates magma flowing upward through a vertical dike 10 kilometers long. The model includes factors such as fluid shear stress—the stress generated by two surftaces rubbing against each other—and elastic deformation. Next, they ran simulations of two different scenarios: one in which the magma reservoir feeding the volcanic conduit simply emptied out without refilling and another in which magma flowed up from below, refilling the reservoir.

They found that the relative balance between conduit widening, elastic deformation, and the decreasing trend of magma reservoir overpressure controls the evolution of effusion rate and eruption duration. When a magma reservoir is replenished, it causes a sharp increase in magma reservoir pressure and in erosion rate along the conduit. These changes could even lead to a 30% faster effusion rate at first, but as the conduit in the model widens and pressure in the magma reservoir decreases, the effusion rate is expected gradually to decline. Given the difficulty of measuring the activity of magma reservoirs directly, such data could help scientists better understand Kīlauea and other effusive eruptions, the team writes. (*Geophysical Research Letters*, https://doi.org/10.1029/2018GL077806, 2018) **—Emily Underwood, Freelance Writer**

Hydrology Dictates Fate of Carbon from Northern Hardwood Forests

EOS CENTENNIAL COLLECTION

In Canada's northern hardwood forests, shown here surrounding Cache Lake in Ontario, hydrologic connectivity drives carbon export from the ecosystem. Credit: Ptrbnsn, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

From forested coastal wetlands to northern boreal forests, forests are considered essential cogs in the global carbon cycle. Generally, forests act as "sinks" by absorbing more carbon from the atmosphere through photosynthesis than they release, but they still do emit a considerable amount of carbon dioxide. Much of this release happens through respiration by soil microbes.

However, not all carbon lost by forests escapes to the atmosphere. A small but significant amount is exported into aquatic systems via dissolved organic carbon, which derives from soil material like plant litter and peat. Compared with atmospheric carbon export, aquatic export is small, but it is still considered a critical carbon flux.

In a new study, *Senar et al.* investigated how hydrologic connectivity controls carbon transport in the ecosystem and how carbon is partitioned between the atmosphere and waterways in Canada's northern hardwood forests. The researchers hypothesized that hydrologic connectivity—the water-mediated transfer of matter and energy between landscape positions—determines carbon's fate in the ecosystem. The flow of water between habitat types is closely tied to soil moisture, water table depth, and stream discharge.

The research took place in the Turkey Lakes Watershed, an experimental watershed located approximately 60 kilometers north of Sault Ste. Marie in Ontario, Canada. The researchers collected stream samples for 5 years to monitor dissolved organic carbon, and they monitored carbon dioxide emissions using flux chambers placed across habitat types. Other measurements included soil temperature, moisture, and organic carbon.

The results indicated that hydrologic connectivity between uplands, ecotones (regions of transition), and wetland habitats does indeed control the fate of carbon—both atmospheric and aquatic—in the northern hardwood forest. However, the study unexpectedly found that hydrological connectivity also dictates the magnitude of carbon exported from the ecosystem. In water-limited habitats, like uplands, the increase in soil water stimulated microbial activity and, subsequently, carbon dioxide released from respiration. In contrast, as wetlands and other water-saturated areas became hydrologically linked to the surrounding uplands, the increase in soil water tamped down the soil bacteria liveliness in the resulting anaerobic soils.

The study also found that hydrologically connected habitats resulted in an increase in aquatic transport of carbon. In other words, as more water entered the ecosystem, more carbon washed downstream into streams and lakes. The findings showed a distinct seasonal pattern, with increased aquatic transport during periods of high hydrologic connectivity, namely, spring snowmelts and fall storms.

Future climate predictions project a trend toward higher temperatures and prolonged periods of disconnected hydrology. The authors suggest that under those circumstances, northern hardwood forests will initially increase atmospheric carbon emissions from upland and ecotone habitats, with an eventual decrease as water becomes limited. The reduction in hydrologic connectivity will also result in less aquatic carbon transport downstream. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2018JG004468, 2018) **—Aaron Sidder, Freelance Writer**

Regional Metamorphism Occurs Before Continents Collide

While studying rocks in the Scottish Highlands in the late 1800s, George Barrow mapped a sequence of mineral zones representing increasingly higher grades of metamorphism at inferred increasing temperature and depth in Earth. Now known to represent the most common type of regional metamorphism, the Barrovian sequence has been widely documented in areas that experienced the elevated temperatures associated with continental collision and other tectonic deformation.

Barrovian metamorphism is distinguished by a high vertical temperature gradient that when extrapolated, yields temperatures of 800°C–850°C at the base of 35-kilometer-thick crust, nearly double that of stable continental areas. Previous research has found a number of mechanisms to explain these high temperatures, including frictional heating, magmatism, and underthrusting of crust containing abundant radioactive heat generation. However, none of these mechanisms are entirely consistent with field evidence showing that some regional metamorphism occurs prior to or during deformation—or with the fact that only lithosphere that is already warm is weak enough to be deformed by the forces generated at plate boundaries.

Hyndman proposes a new theory to overcome the problems of these previous explanations. Namely, the high temperatures responsible for Barrovian metamorphism are not caused by heat generated during and after deformation; instead, the temperatures predate continental collision and other tectonic deformation.

According to the author, the high temperatures have their origin in precollision hot back arcs—broad areas, up to 1,000 kilometers wide, found landward of the subduction zones that must occur on at least one side as continents converge and oceans close. This idea is based on recent observations that most modern subduction zones have uniformly hot back arcs with thin lithospheres and vertical temperature gradients that are remarkably consistent with Barrovian metamorphism. Most collision deformation and regional metamorphism around the world are concentrated in former hot, weak back arcs, which had Barrovian temperature gradients prior to ocean closure and collision.

Glencoe in the Highlands of Scotland, where geologist George Barrow first recognized Barrovian geological regional metamorphism. Credit: iStock.com/iweta0077

By concluding that regional metamorphism and deformation can result from back-arc crust that was already heated to high temperatures prior to deformation, this paper offers an innovative vision of the thermal structure of many ancient and modern collision zones. *(Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2018GC007650, 2018) **—Terri Cook, Freelance Writer**

The Oxygen Neutral Cloud Surrounding Jupiter's Volcanic Moon

Dotting the surface of Jupiter's moon Io are lakes of lava and hundreds of volcanoes, some spewing lava dozens of kilometers into the air. Only slightly larger than our own planet's moon, Io is the most volcanically active place in the solar system. Its thin atmosphere is made up largely of sulfur oxides. As Io orbits Jupiter, neutral gas particles escape its atmosphere and collide with electrons, giving rise to a donut-shaped cloud of ionized particles around Jupiter known as the Io plasma torus.

Exactly how those neutral gases escape Io's atmosphere is not well understood, however. Previous studies have shown that most atomic oxygen and sulfur escape Io's atmosphere by colliding with energetic particles, such as torus ions, which bump the particles out of the atmosphere in a process known as atomic sputtering. Some of the particles escape from Io's gravity and form clouds of neutral sulfur and oxygen. *Koga et al.* provide new insights into the role of the neutral cloud in the Io plasma torus.

The researchers took advantage of data collected by Japan's Hisaki satellite, which was launched in 2013 and became the first space telescope to observe planets like Mars and Jupiter from Earth's orbit. They used spectrographic data from the Extreme Ultraviolet Spectroscope for Exospheric Dynamics (EXCEED) instrument aboard the satellite to measure atomic emissions at 130.4 nanometers around Io's orbit. The measurements were collected over 35 days between November and December 2014, a relatively calm volcanic period for the moon.

The authors found that Io's oxygen cloud has two distinct regions: a dense area that spreads inside Io's orbit, called the banana cloud, and a more diffuse region, which spreads all the way out to 7.6 Jovian radii. They plugged the satellite observations into an emissions model to estimate the atomic oxygen number density. The researchers found more oxygen inside Io's orbit than previously thought, with a peak density of 80 atoms per cubic centimeter at a distance of 5.7 Jovian radii. They also calculated a source rate of 410 kilograms per second, which is consistent with previous estimates.

This study provides the first good look at Io's neutral cloud, which has historically been too dim to measure. Neutral particles from Io's atmosphere are one of the primary sources for charged particles in Jupiter's massive magnetosphere. Ultimately, the authors note, a better understanding of the neutral cloud will provide important insights into the gas giant's magnetosphere. *(Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2018JA025328, 2018) **—Kate Wheeling, Freelance Writer**

Upper Estuaries Found to Be a Significant Blue Carbon Sink

EOS CENTENNIAL COLLECTION

From a vantage point during low tide, bald cypress trees line this moderately salt influenced (approximately 1.4 practical salinity units) tidal freshwater forested wetland on Butler Island in the Waccamaw River in South Carolina. Credit: Nicole Cormier, USGS

Wetlands play an outsized role in global carbon cycling. The world's wetlands store as much as 30% of terrestrial carbon, sequestering nearly 50 million metric tons of carbon from the atmosphere every year.

Although extensive peatlands in Alaska and Canada drive much of this storage, in recent years researchers have determined that blue carbon wetlands—those found in coastal ecosystems—store more carbon than their limited size would suggest. Should sea levels continue to rise as projected, blue carbon wetlands are expected to play a growing role in global carbon calculations.

To understand how transitions in coastal ecosystems will affect carbon budgets, *Krauss et al.* studied how carbon is stored, sequestered, and transported in estuaries in the southeastern United States. The researchers specifically looked at tidal freshwater forested wetlands and low-salinity marshes, two neighboring habitats in the upper estuary that may transform as ocean water encroaches farther inland in the coming decades. The study is the first to explore the carbon dynamics across these coastal environments, which occur around the world.

The researchers established transects along two rivers: the Waccamaw River in South Carolina and the Savannah River in Georgia. The transects spanned four wetland types characterized by freshwater to low-salinity conditions. (The salinity of low-salinity, or oligohaline, marshes is approximately 5.0 practical salinity units. In comparison, the salinity of marine environments is approximately 30.0 practical salinity units.) At each wetland, the scientists recorded the aboveground carbon stock housed in the trees, shrubs, herbaceous plants, and downed woody debris and the belowground carbon stock in soils, including plant roots and sediments. They also measured the flux of carbon between the soil, vegetation, and atmosphere and tracked how carbon moves between habitats.

The researchers found that the upper estuary habitats store more carbon than several well-known carbon sponges, like boreal and temperate forests. Surprisingly, they also discovered that the upper estuary carbon stocks even exceed those of seagrass and salt marsh ecosystems, two celebrated coastal carbon sinks.

However, the tidal freshwater forested wetlands and marshes differed in how they stored carbon. Whereas the tidal freshwater forests store an appreciable amount of carbon in aboveground woody material, the carbon generally migrates belowground into the roots and soil as salinity increases downstream and herbaceous vegetation becomes more prominent. The more saline lower reaches of the transects also appear to store more carbon than their upstream counterparts.

Although whether similar wetlands behave comparably in different parts of the world is still unknown, the research positions upper estuarine wetlands as carbon storage, sequestration, and flux powerhouses. These tidal wetlands could play an important role in mitigating climate change. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2018GB005897, 2018) **—Aaron Sidder, Freelance Writer**

Interdisciplinary

ASSISTANT PROFESSOR

Field-Oriented Sedimentology, Structural Geology, or Volcanology

The Nevada Bureau of Mines and Geology (NBMG) at the University of Nevada, Reno, seeks applicants for a tenure-track academic faculty position in field-oriented research in structural geology, volcanology, or sedimentology. NBMG is a public service unit of UNR and serves as both the state geologic survey of Nevada and as a research department in the UNR College of Science. Faculty at NBMG have tenure-track academic appointments, with both research and teaching obligations.

Position Responsibilities: The primary responsibilities of this position will be to develop broad programs in research and education in Sedimentology, Structural Geology, or Volcanology. Research will focus on the geologic framework and tectonic evolution of Nevada, utilizing innovative approaches to detailed geologic mapping, sedimentologic analysis, structural analysis, geochronology (e.g. U/Pb, detrital zircons, or $^{40}Ar/^{39}Ar$), and/or paleomagnetism. Position responsibilities and expectations include: 1) utilizing detailed geologic mapping to conduct basic and applied research; 2) working independently as well as collaboratively with NBMG faculty-staff, faculty in other geoscience units in the Nevada system of higher education, and others in industry and government in developing funded research projects; 3) contributing to the understanding of natural resources and geologic hazards in the region; 4) supervising graduate students and teaching courses in the successful candidate's area of expertise.

Qualifications: Applicants must have a doctorate in geology or a related geoscience field by the time of hire and a demonstrated record of research on topics related to sedimentology, structural geology, tectonics, and/or volcanology as indicated by dissertation research, industry experience, or peer-reviewed publications. The successful candidate must also have experience in field-oriented research and a desire to conduct detailed geologic mapping on future projects in Nevada. Excellent communication skills, as demonstrated in written application materials; commitment to public service; potential for, or established record of publications; and ability to attract funding are essential. Doctoral research must include one or more of the following disciplines: structural geology, sedimentology, or volcanology. We encourage candidates to explain achievable plans for funded research on Nevada-focused topics in their area of expertise in the letters of interest.

Salary and Date of Appointment: The position will be a tenure-track faculty appointment at the assistant professor level with an academic-year base salary that is competitive with other research universities. Starting date will be July 1, 2019 or shortly thereafter, depending on availability of the successful candidate.

For more detailed information about the position and to apply, please visit: https://is.gd/pgqdbK. Application deadline is March 1, 2019. For further information about NBMG, please consult our website http://www.nbmg.unr.edu.

The University of Nevada, Reno is committed to Equal Employment Opportunity/Affirmative Action in recruitment of its students and employees and does not discriminate on the basis of race, color, religion, sex, age, creed, national origin, veteran status, physical or mental disability, and sexual orientation. The University of Nevada employs only United States citizens and aliens lawfully authorized to work in the United States.

EEO/AA Women and under-represented groups, individuals with disabilities, and veterans are encouraged to apply.

Assistant or Associate Professor – Economic Geologist (Hydrothermal Geochemistry)

Nevada Bureau of Mines and Geology

The Nevada Bureau of Mines and Geology (NBMG) at the University of Nevada, Reno is seeking applications for a tenure-track faculty position focused on hydrothermal geochemistry and mineral deposits. NBMG is a research and public service unit of the University of Nevada, Reno (UNR) and is the state geological survey. Managed as part of the Mackay School of Earth Sciences and Engineering in the College of Science at UNR, NBMG functions as an academic unit, and its principal scientists are tenure-track faculty members. Nevada is one of the most exciting regions in the world to do research in the geosciences and the best in the U.S. for the study of hydrothermal mineral deposits. For further information about NBMG, please consult our website http://www.nbmg.unr.edu.

Interested applicants must have a doctorate in geology or a related geoscience field by the time of hire and a demonstrated record of research on topics related to hydrothermal mineral deposits as indicated by dissertation research or peer-reviewed publications. Excellent communication skills, as demonstrated in written application materials; commitment to public service; potential for, or established record of publications; and ability to attract funding are essential. Previous research must include economic geology or hydrothermal geochemistry with a focus on mineral deposits.

Preference will be given to candidates with: 1) academic experience in hydrothermal mineral deposits, particularly research that blends both quantitative analytical and field-based approaches; 2) demonstrated research productivity with publications in the peer-reviewed literature; and 3) achievable plans for funded research on Nevada-focused topics in economic geology, as described in the applicant's letter of interest. Additional preferred fields of expertise include: 1) geochemistry of metal solubility and transport; 2) geochemical modeling, 3) fluid inclusions, 4) stable isotopes, and/or 5) geochemical microanalyses

Position responsibilities and expectations include: 1) working independently as well as collaborating with NBMG faculty-staff, faculty in other geoscience units at UNR and UNLV, and others in industry and government in developing funded projects and conducting research; 2) focusing research on mineral deposits in Nevada, though some research can be conducted outside Nevada; and 3) supervising graduate students and teaching courses related to hydrothermal geochemistry.

The position will be a tenure-track faculty appointment with an academic-year base salary (9 months) that is competitive with other research universities. Starting date will be July 1, 2019 or shortly thereafter, depending on availability of the successful candidate.

For more detailed information about the position, and to apply, please visit

https://nshe.wd1.myworkdayjobs.com/en-US/UNR-external/job/University-of-Nevada-Reno-Main-Campus/Assistant-or-Associate-Professor-Economic-Geologist_R0113408-1. Applications will be accepted through February 21, 2019.

EEO/AA Women, under-represented groups, individuals with disabilities, and veterans are encouraged to apply.

Physicists, Applied Mathematicians, and Electrical Engineers

NorthWest Research Associates (NWRA; www.nwra.com) is a scientific research organization, owned and operated by its Principal Investigators, with expertise in the geophysical and space sciences. The nine current Ph.D. physicists and electrical engineers composing NWRA's Monterey, California location are respected experts in radiowave propagation and signal processing for radar and communication systems, ionospheric modeling, and signal scattering in randomly structured ionization. We are looking for physicists, applied mathematicians, and EEs, preferably at the Ph.D. level, to support several interesting new projects involving propagation modeling and signal processing for ionosphere and space-weather modeling. A strong ability in applied mathematics, especially inverse problems, is desirable.

New hires will work closely with our seasoned scientists on existing projects; early-career scientists would gain in further career growth from mentorship by world-class experts. NWRA provides a supportive environment for scientists who have a passion for their research, a desire to continue learning, and who enjoy communicating their research and research ideas through papers, presentations, and proposals. NWRA scientists can eventually become Principal Investigators of their own projects and co-owners of NWRA. US Citizenship is required.

NWRA offers a full benefit package including health, life, disability, and long-term care insurance and matching 401K contributions. Please send resumés to HR@nwra.com.

NWRA is an Equal Opportunity Employer for minority, women, veterans and disabled candidates.

Michel T. Halbouty '30 Visiting Chair in Geology and Geophysics

The Department of Geology and Geophysics at Texas A&M University is pleased to announce the Michel T. Halbouty '30 Visiting Chair (Visiting Professor) in Geology and Geophysics. The purpose of Mr. Halbouty's generous gift is to 'Promote excellence in the teaching and research of the Department of Geology and Geophysics.' Candidates should have a PhD in Geology, Geophysics or related field, be at the Associate or Full Professor rank or hold an equivalent title, and be highly accomplished scholars with an internationally recognized record of excellence in their field of study. Chair holders should plan to be at the Texas A&M College Station campus and engage with department faculty and students in research and teaching for up to twelve months duration. The appointment may include partial salary support, housing and travel expenses, and expenses related to proposed teaching, research, and engagement activities.

The College of Geosciences at Texas A&M University is a unique institution committed to fundamental Earth systems research across four Departments: Atmospheric Sciences, Geography, Oceanography, and Geology and Geophysics. The College hosts the Texas Sea Grant, the Geochemical and Environmental Research Group (GERG), and the International Ocean Discovery Program (IODP). This appointment includes the opportunity to work across departments and programs in the College and lead international coursework to maximize educational opportunities for our undergraduate and graduate students.

The Texas A&M System is an Equal Opportunity/Affirmative Action/Veterans/Disability Employer committed to diversity.

Interested candidates should submit electronic applications to: https://apply.interfolio.com/57956 Applications should be submitted by March 31, 2019 to be considered for awards beginning in 2019 or 2020. Applicants should identify and coordinate with faculty proponents prior to submitting an application. Applications should include a CV; a 2-page proposal identifying the faculty proponent and research, teaching and engagement activities as a Visiting Chair holder; a timeline of availability for visiting the department; and a budget tabulation and justification of desired funds needed for salary and other expenses. Please contact the search chair, Dr. Ryan Ewing, at rce@tamu.edu with questions.

Ocean Sciences

Geological Oceanography Assistant Professor

The School of Ocean Science and Engineering (SOSE) at The University of Southern Mississippi (USM) invites qualified applicants for a full-time, nine-month, tenure-track position as an assistant professor in Geological Oceanography, broadly defined, to join the Marine Science faculty in the Division of Marine Science. The SOSE includes two academic divisions, Marine Science, and Coastal Sciences, and several R&D centers including: Hydrographic Science Research Center, Center for Fisheries Research and Development, and Thad Cochran Marine Aquaculture Center. The Division of Marine Science is based at the NASA Stennis Space Center where Marine Science faculty benefit from close working relationships with a number of on-site federal agencies, including the Naval Research Laboratory-Stennis Space Center, the Naval Oceanographic Office, the Naval Meteorology and Oceanography Command, the USGS and NOAA, including the National Data Buoy Center.

Marine Science graduate and undergraduate programs extend across traditional marine science emphasis areas in biological, physical, chemical and geological oceanography, as well as hydrographic science and ocean engineering. Marine Science faculty and graduate programs are housed at Stennis Space Center, where the M.S. and Ph.D. degrees in Marine Science and the M.S. degree in Hydrographic Science are delivered. The Marine Science and Ocean Engineering B.S. degree programs are delivered at the USM Gulf Coast Campus in Long Beach, MS as well as at USM's main campus in Hattiesburg, MS. The Long Beach campus is in close proximity to the Port of Gulfport, which is the home port for USM's R/V Point Sur and the recently opened USM Marine Research Center, that features a state-of-the-art fabrication lab, testing tank, and laboratory space.

Applicants must hold a Ph.D. in earth science, oceanography, or a related field. Preference will be given to candidates with post-doctoral experience, and a demonstrated record of scholarship, service, grant development, communication, and commitment to diversity. The successful candidates are expected to develop and deliver courses in their field of specialization. The successful candidate should demonstrate the potential to contribute across disciplines and promote the continued interdisciplinary growth of the academic and research programs within SOSE. Applicants should submit a letter of interest outlining their qualifications for the position,including a research plan, teaching philosophy with a curricular plan, a curriculum vitae, and names and contact information of at least four references. Salary packages will be nationally competitive and commensurate with experience. Applications must be submitted online at https://usm.csod.com/ats/careersite/jobdetails.aspx?site=1&c=usm&id=597. For inquiries about the position, contact Davin Wallace, Chair of the Search Committee, at 1-228-688-3060 or davin.wallace@usm.edu. Review of applications begins 1 March 2019 and continues until the position is filled, with an anticipated start date of August 2019.

EOE/F/M/VET/DISABILITY

COLLEGE of ENGINEERING
UtahStateUniversity

DIRECTOR OF THE UTAH WATER RESEARCH LAB

The College of Engineering of Utah State University is seeking a dynamic individual with strong leadership skills, knowledge, and experience in water and environmental research to fill the position of Director of the Utah Water Research Laboratory (UWRL). The UWRL Director reports directly to the Dean of the College of Engineering and is typically a tenured faculty member of the Civil and Environmental Engineering (CEE) Department with the rank of Professor. The UWRL Director is responsible for managing fiscal and personnel resources at the UWRL, requiring a broad knowledge of operations, external funding, contracts and grants, project management, personnel management, and business development. This position requires close relationships with Colleges outside of Engineering such as Agriculture and Natural Resources together with state and federal agencies and other stakeholders relevant to water and environmental interests.

The UWRL has been a national and international leader in water and environmental research for over 50 years. As the oldest and one of the largest university-based water research facilities in the U.S., the UWRL is a unique facility capable of providing state-of-the-art laboratory space and research support for large-scale hydraulic and physical modeling and testing, water resources and hydrology studies, and environmental research. Housed in two buildings, UWRL facilities comprise 113,000 square feet of laboratory, computer, and office space for faculty, students, and staff. In addition to two world-class hydraulics laboratories, the UWRL also houses a state-of-the-art environmental quality analytical laboratory with instrumentation and capabilities for analyses of samples across environmental media (water, soil, and air). Funding to support UWRL activities is available from the State of Utah through Utah Mineral Lease and state appropriated funds, as well as through external research contracts and grants. Faculty within the Water and Environmental Engineering programs within the CEE Department are partly supported by the UWRL to promote research relevant to the state and also promote interdisciplinary research within and outside of Utah. More information about the UWRL is available at **uwrl.usu.edu.** Inquires about the position should be directed to Professor Thom Fronk, thomas.fronk@usu.edu

To apply visit **https://usu.hiretouch.com/job-details?jobID=4060**

Review of applications will continue until the position is filled.

Postcards from the Field

Dear AGU:

Today the Sun rises over the end of our 3 weeks in Alberta, Canada. Our team has been measuring the natural background spring–summer–fall carbon dioxide (CO_2) and methane (CH_4) cycles in the boreal forest in Alberta, as well as net emissions from oil sands and oil and gas processing facilities and fields.

Not only were we taking in situ measurements of CH_4, CO_2, carbon monoxide, ozone, and water from these sites using our onboard Picarro via aircraft, but also we were taking air samples using flask packages for later analysis of over 50 different species of trace gases. Lots of good science was done, but it is nice to be heading home! Until next time, Alberta.

—**Mackenzie Smith,** Scientific Aviation, Boulder, Colo.

View more postcards at *bit.ly/Eos_postcard*


AGU
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"The more opportunities there are to get students involved, the more you will encourage previously unreached and unrepresented groups to join the Earth and Space science community."
Ryan Haupt
Research Fellow, Smithsonian Museum of Natural History
2015 Student Travel Grant Recipient
Support the next generation of Earth and space scientists.
Donate to the Austin Student Travel Grant Challenge.
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