Eos

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EARTH & SPACE SCIENCE NEWS

Our Magnetic Brains

Los Angeles's Shaky Underbelly

Beavers: Nature's Firefighters

Up in Smoke

As wildfires scorch the land, scientists are using novel methods to study the damage to our air.

AGU 100
ADVANCING EARTH AND SPACE SCIENCE

Finding Wildfire's Fingerprint in the Atmosphere

Wildfires seem to be everywhere in the news lately. For those of us in the United States, and particularly in California, "wildfire season" evokes a clear sense of dread, having personally touched so many us. (I have several friends who lost homes—thankfully, though, nothing more—during the 2017 Thomas Fire in my hometown.) As the calendar turned over to 2020, wildfires in Australia had burned more than 10 million acres in a month—at what was only the start a blazingly hot and dry summer. In Indonesia, ultrafine particles from agricultural practices that ignite peatlands have serious effects on the health of tens of thousands of people in the region each year.

The air is filling with smoke. Scientists, gratefully, are busy figuring out the answers to all our questions: What is the smoke made of, where is it all going, and *just how bad is it*? We've compiled this special issue of *Eos* to take a close look at the growing field of wildfire emissions research, pulling in experts from across a dozen disciplines of the geosciences.

Ralph Kahn of NASA Goddard Space Flight Center offers us "A Global Perspective on Wildfires" on page 18. An expert on aerosols and remote sensing technology, Kahn describes the many satellite instruments being used to study wildfire emissions today. Scientists are overcoming the disadvantages of observations from space from any one satellite (e.g., relatively low resolution, narrow observation bands, orbital paths that limit revisits) by combining data from what are now a wealth of instruments overhead. The gaps in these low-Earth-orbit observations of smoke plumes, in both spatial and temporal coverage, can also be filled in by chemical transport models; the models themselves can be constrained and validated by the observational data. With each pass overhead, our Earth observers are giving us a clearer picture of smoke emissions and how they travel through the atmosphere.

A major challenge right now is figuring out the effects of wildfires on global climate, and the reverse: the changing climate's effect on wildfires. On page 30 ("Firing Up Climate Models"), you'll meet the FIREX-AQ team flying over the western United States in a DC-8, trying to collect enough information to more accurately incorporate fires into global climate models. It's a herculean job when one considers the wild variations of fires in size, biomass fuel, and, of course, whether they're ignited by human or natural sources. Most models today don't even attempt to incorporate them, but FIREX-AQ and several other teams in our feature story believe that understanding wildfires is crucial to truly understanding—and forecasting—our climate.

For a bit of respite from these disasters, turn to page 12 ("Beavers: Nature's 'Little Firefighters'") to learn about some habitat protection provided by our favorite dam builders. Ecohydrologist Emily Fairfax searched through records of forest fires in North America that occurred near beaver habitats and discovered that their dams acted as irrigation channels, keeping nearby vegetation insulated from the flames. Be sure to visit this news story online to view the stop-motion animation Fairfax created to illustrate the beavers' influence on their wooded surroundings (bit.ly/natures-firefighters).

Visit us at Eos.org for all these articles and many more as part of our wildfire emissions special coverage through February.

Heather Goss, Editor in Chief

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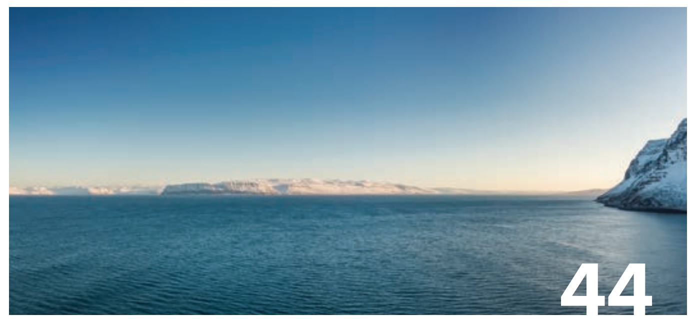
Wildfires in Russia, seen here, burned so large and so close to population centers in 2019 that several Siberian cities were choked under clouds of smoke for days. Credit: Anton Petrus/ Moment/Getty Images



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Using Satellites and Supercomputers to Track Arctic Volcanoes

Conical clues of volcanic activity speckle the Aleutian Islands, a chain that spans the meeting place of the Pacific Ring of Fire and the edge of the Arctic. (The chain also spans the U.S. state of Alaska and the Far Eastern Federal District of Russia.) Scientists are now turning to advanced satellite imagery and supercomputing to measure the scale of natural hazards like volcanic eruptions and landslides in the Aleutians and across the Arctic surface over time.

When Mount Okmok in Alaska unexpectedly erupted in July 2008, satellite images informed scientists that a new 200-meter cone had grown beneath the ashy plume. But scientists suspected that topographic changes didn't stop with the eruption and its immediate aftermath.

For long-term monitoring of the eruption, Chunli Dai, a geoscientist and senior research associate at the Ohio State University, accessed an extensive collection of digital elevation models (DEMs) recently released by ArcticDEM, a joint initiative of the National Geospatial-Intelligence Agency and the National Science Foundation. With ArcticDEM, satellite images from multiple angles are processed by the Blue Waters petascale supercomputer to provide elevation measures, producing high-resolution models of the Arctic surface.

Dai first used these models to measure variations in lava thickness and estimate the volume that erupted from Tolbachik volcano in Kamchatka, Russia, in work published in *Geophysical Research Letters* in 2017 (bit.ly/measure-lava). The success of that research guided her current applications of ArcticDEM for terrain mapping.

Monitoring long-term changes in a volcanic landscape is important, said Dai. "Ashes easily can flow away by water and by rain and then cause dramatic changes after the eruption," she said. "Using this data, we can see these changes…so that's pretty new."

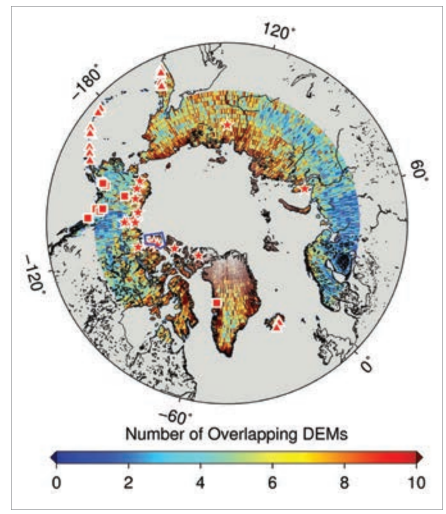
Creating time series algorithms with the ArcticDEM data set, Dai tracks elevation changes from natural events and demonstrates the algorithms' potential for monitoring the Arctic region. Her work has already shown that erosion continues years after a volcanic event, providing first-of-their-kind measurements of posteruption changes to the landscape. Dai presented this research at AGU's Fall Meeting 2019 in San Francisco, Calif. (bit.ly/DEMs-land-surface).

Elevating Measurement Methods

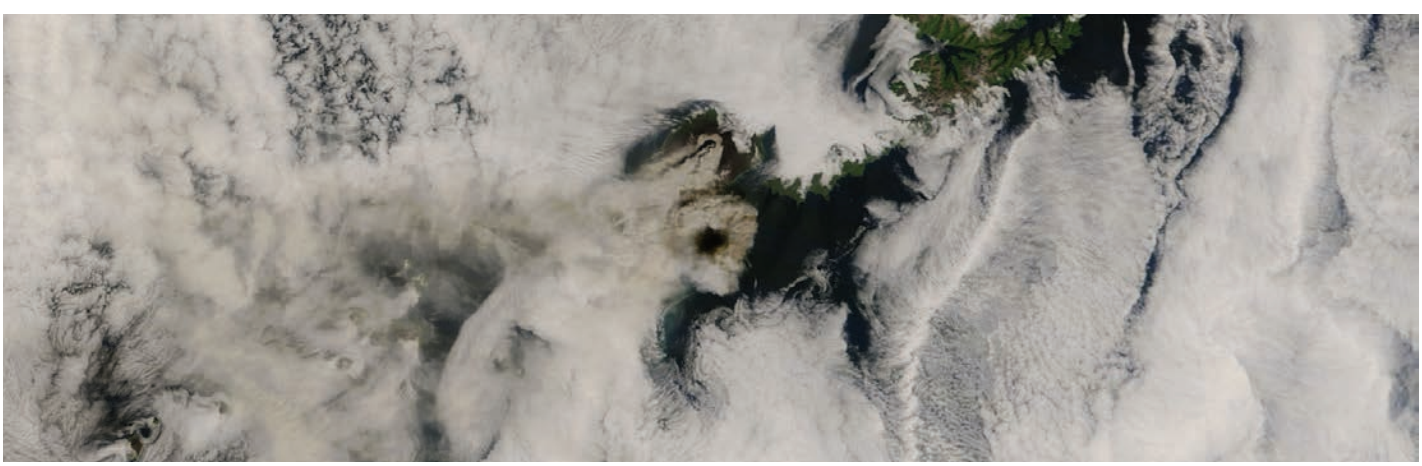
"This is absolutely the best resolution DEM data we have," said Hannah Dietterich, a research geophysicist at the U.S. Geological Survey's Alaska Volcano Observatory not involved in the study. "Certainly, for volcanoes in Alaska, we are excited about this."

Volcanic events have traditionally been measured by aerial surveys or drones, which are expensive and time-consuming methods for long-term study. Once a hazardous event occurs, Dietterich explained, the "before" shots in before-and-after image sets are often missing. Now ArcticDEM measurements spanning over a decade can be used to better understand and monitor changes to the Arctic surface shortly following such events, as well as years later.

For example, the volcanic eruption at Okmok resulted in a sudden 200-meter elevation gain from the new cone's formation



In this map of ArcticDEM coverage, warmer colors indicate more overlapping data sets available for time series construction. Blue and red rectangles mark mass wasting events, triangles identify volcanoes, and red stars show locations of active layer detachments and retrogressive thaw slumps, both used for studying landslides. Credit: Chunli Dai



The 2008 Okmok eruption in Alaska resulted in a new volcanic cone, as well as consistent erosion of that cone's flanks over subsequent years. The volcano's ring-shaped plume is visible in the center of this satellite image. Credit: NASA image courtesy of Jeff Schmaltz, MODIS Rapid Response Team, NASA Goddard Space Flight Center but also showed continuing erosion rates along the cone flanks of up to 15 meters each year.

Landslides and Climate

For Dai, landslides provide an even more exciting application of ArcticDEM technology. Landslides are generally unmapped, she explained, whereas "we know the locations of volcanoes, so a lot of studies have been done."

Mass redistribution maps for both the Karrat Fjord landslide in Greenland in 2017 (bit.ly/Karrat-Fjord) and the Taan Fiord landslide in Alaska in 2015 (bit.ly/Taan-landslide) show significant mass wasting captured by DEMs before and after the events.

"We're hoping that our project with this new data program [will] provide a mass wasting inventory that's really new to the community," said Dai, "and people can use it, especially for seeing the connection to global warming."

Climate change is associated with many landslides studied by Dai and her team, who focus on mass wasting caused by thawing permafrost. ArcticDEM is not currently intended for predictive modeling, but as more data are collected over time, patterns may emerge that could help inform future permafrost loss or coastal retreat in the Arctic, according to Dietterich. "It is the best available archive of data for when crises happen."

> **"If we can measure [the changing Arctic environment], then we can get the linkage between global warming and its impact on the Arctic land."**

Global climate trends indicate that Arctic environments will continue to change in the coming years. "If we can measure that, then we can get the linkage between global warming and its impact on the Arctic land," said Dai.

By **Lara Streiff** (@laragstreiff), Science Communication Program Graduate Student, University of California, Santa Cruz

Will Melting Sea Ice Expose Marine Animals to New Diseases?

Northern sea otters are just one of many marine mammal species that can contract the phocine distemper virus (PDV), which is related to the canine distemper virus. Credit: U.S. Environmental Protection Agency

In 2004, Tracey Goldstein was trying to crack a marine mammal mystery. Goldstein, associate director of the One Health Institute at the University of California, Davis School of Veterinary Medicine, was part of a team digging for answers about why Alaska's northern sea otter populations were plummeting.

The falling number of otters was curious. Before the decline began, decreases in the killing of otters for the fur trade had actually sparked a population rebound, Goldstein said.

Researchers still don't know exactly what made the otter populations dwindle. However, Goldstein was shocked by something she and her colleagues discovered while screening the animals for a variety of diseases. Some of the animals had been exposed to the phocine distemper virus (PDV), which is pathogenic for pinnipeds and is closely related to the measles virus and the canine distemper virus.

Same Virus, Different Location

This wasn't the first time researchers identified a PDV outbreak in marine mammals. An estimated 23,000 European harbor seals were killed after they were sickened by the virus in 1988. In 2002, a second epidemic hit the northern Atlantic Ocean, killing approximately 30,000 harbor seals.

However, this was the first time a PDV outbreak was confirmed in the northern Pacific Ocean.

Northern sea otters "don't move widely," said Goldstein, so the emergence of PDV in the Alaskan population "really surprised" her and her colleagues. Researchers realized the virus was likely transmitted to the otters by some species of marine mammal that had contact with European harbor seals exposed to the virus. "Nomadic Arctic seals with circumpolar distributions (e.g., ringed and bearded, Erignathus barbatus, seals) and geographic ranges that intersect with those of harp seals, may be carriers of PDV to the North Pacific," researchers write in *Scientific Reports* (bit.ly/PDV-mammals).

This explanation presented one big problem: Contact between Arctic and sub-Arctic seal species was assumed to be impossible due to Arctic sea ice separating the species. This left the team wondering whether there could be a connection between the rapid melting of Arctic sea ice, driven by climate change, and the emergence of PDV in the otters.

Boundaries Melting Away

In an international study conducted between 2001 and 2016, Goldstein and her colleagues probed connections between virus transmission patterns and environmental factors to understand when and how PDV was introduced into the North Pacific.

"The study is ambitious in its interdisciplinary effort to summarize immunological data on prevalence of antibodies to PDV, molecular data on the PDV strain, and data on animal behavior and migration patterns" with ice extent data, said Karin Hårding, an associate professor of biology and environmental studies at the University of Gothenburg in Sweden. Hårding wasn't involved with the study.

In 2004, scientists confirmed the first instance of a phocine distemper virus outbreak in the northern Pacific Ocean.

Researchers collected nasal swab and blood samples from 2,530 live animals, including northern sea otters, ice-associated seals (including bearded, ribbon, spotted, and ringed seals), northern fur seals, and Steller sea lions. They also collected blood and tissue samples from 165 dead animals found on beaches or that people had hunted for food. The researchers then screened the samples for active infection and the presence of antibodies, which signify past exposure.

In addition, researchers "incorporated satellite telemetry data from ongoing ecological studies of seals and Steller sea lions, which provided a unique opportunity to combine animal movement and epidemiologic data to understand the potential spread of PDV," they write.

The scientists noticed two spikes in Pacific PDV exposure and infection: one from 2003 to 2004 and another in 2009. August or September of 2002 and 2008 were months with reduced amounts of Arctic sea ice, resulting in the opening of water routes between Russia's Arctic coast and the Pacific Ocean.

Furthermore, in both 2001 and 2007, "sea ice blocked passage through at least part of the Arctic Ocean bordering Russia's coast," the researchers note. "When controlling for animal group and age class, presence of an open water route along the northern Russian coast following a year in which the Arctic sea ice along the Russian coast was closed was significantly associated with PDV exposure or infection," they add.

Goldstein thinks that the PDV case provides the first documented connection between reduced sea ice coverage and the emergence of a virus in a marine mammal species.

Hårding was more cautious. The relationships between phenomena like ice coverage of the Arctic basin and the prevalence of antibodies "will always be correlations but do not prove causal relationships," she wrote. "However, the authors do not claim [causation]. They just highlight interesting patterns that coincide," she added.

As sea ice continues to melt in this warming world, will marine species be exposed to other diseases from which they were previously isolated? Only time will tell, but "it has happened once, and there's likely going to be the opportunity for it to happen again," Goldstein remarked.

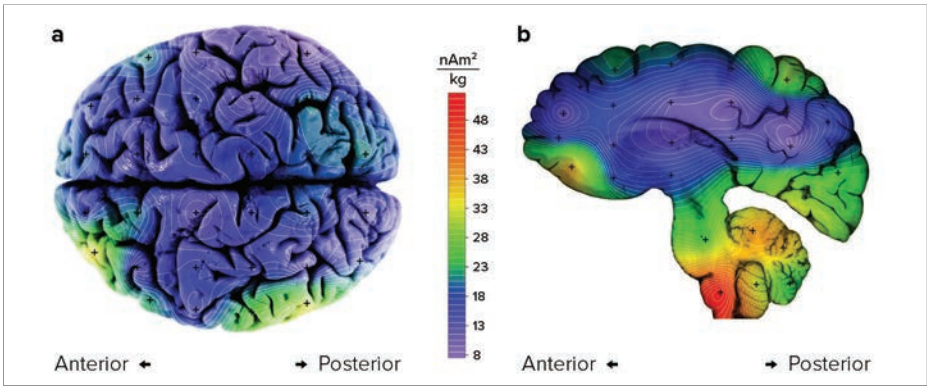
By **Rachel Crowell** (@writesRCrowell), Science Writer

Human Brains Have Tiny Bits of Magnetic Material

Scientists have mapped magnetic materials in human brains for the first time, revealing that our brains may selectively contain more magnetic material in their lower and more ancient regions.

Researchers used seven specimens donated in Germany to measure brain tissue for signs of magnetite, Earth's most magnetic mineral. Scientists have known that other types of life, such as special kinds of bacteria, contain magnetite. But the distribution of magnetite in human brains has been unclear because no systematic study had mapped the mineral in human tissue before.

The results could shine a light on why humans have magnetite in their brains to begin with, which remains an open question. Stuart Gilder, lead author of the study and a scientist at Munich University, said that the team's results show that magnetic particles exist in the "more ancient" part of the brain. "We thought from an evolutionary standpoint, that was important," Gilder said.



Humans have areas of the brain that are more magnetic than other areas. Warm colors show higher levels of magnetic resonance, measured here in nanoampere-square meter (or its magnetic moment) per kilogram of brain tissue. The upper region of the brain, the cerebrum, has low levels. The lower in the brain you go, the stronger the magnetic signal grows and are particularly high in the brain stem. Credit: Gilder et al., 2018, https://doi.org/10.1038/s41598-018-29766-z

Magnetic Minds

Scientists discovered the first hints of magnets in human brains in 1992, when a paper reported that tiny crystal grains, some barely wider than a DNA strand, were found in human brain tissue from seven patients in California (bit.ly/Magnetic-Minds). The crystals looked just like the tiny magnets in magnetotactic bacteria that help them navigate along geomagnetic field lines in lakes and saltwater environments.

No one knows why or how magnetite gets into human brains. Magnetite could serve some physiological function, such as signal transmission in the brain, but scientists are able only to speculate. One study of the frontal cortex of 37 human brains suggests that we breathe in magnetite from the environment through our noses. But other researchers, like Gilder, think magnetite comes from internal sources.

From Rocks to Brains

To find out some answers, Gilder and his team dissected seven brains and measured their magnetic strength and orientation. The brains had been preserved in formaldehyde since the 1990s, when relatives and guardians of the deceased donated them to science. The brains came from four men and three women between the ages of 54 and 87.

Gilder typically studies rocks in his lab to ascertain their geologic history, but his latest study was not so different, he said. "I could essentially apply everything that I do to rock to brains," Gilder said. The scientists cut the preserved brains into 822 pieces and ran each sample through a magnetometer, a machine in their lab used to measure records of Earth's magnetic field in rocks.

Whether Gilder is studying rocks or brains, he measures their magnetism in two steps: First, he tests a material's natural magnetic strength, which will typically be low. (Even if a material contains magnetic particles, their dipoles point in random directions, potentially canceling each other out.)

Second, Gilder uses an electromagnet to apply a strong magnetic field to the sample, which aligns the tiny magnetic particles so that they all face the same direction. "If I measure something that is more magnetic after I've applied a very big magnetic field, that's proof that this material contains magnetic recording particles," Gilder said.

For the brain samples, the comparison revealed that magnetite was in "almost every piece" of the specimens, said Gilder.

"The Exact Same Pattern"

The latest study reveals that the lower regions of the human brain, including the cerebellum and the brain stem, had 2 or more times the magnetic remanence of the upper regions of the brain. The upper regions of the brain compose the cerebrum, which is responsible for reasoning, speech, and other tasks, whereas the lower regions handle muscle movement and autonomic functions like heart rate and breathing.

Gilder said that the pattern emerged in each of the seven brains, and it showed no difference depending on the person's age or sex. The brain stem had consistently higher magnetization than any other region, although only five of the seven brains had intact brain stems.

Joseph Kirschvink, a professor at the California Institute of Technology in Pasadena not involved in the study, said that the work "confirms the biological origin of the brain magnetite." Kirschvink said that the results in the study closely matched research he had performed in his lab, but the latest research has "100 times more data."

The scientists took pains to limit contamination, cutting the samples with a ceramic knife and staging the experiment inside a magnetically shielded room in a forest far from urban pollution. They removed samples with high levels of natural magnetic strength that could have been polluted with fragments of the saw cutting into the donors' skulls many years ago. Even with the potentially contaminated samples removed, the data still showed an anatomical pattern.

Gilder presented the research at AGU's Fall Meeting 2019 in San Francisco, Calif. (bit.ly/human-brain).

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

A Dirty Truth: Humans Began Accelerating Soil Erosion 4,000 Years Ago

In a way, human history is etched in the soil. An international team of researchers recently found evidence that we humans have been leaving our mark on this planet since long before the Industrial Revolution. Around 4,000 years ago, human activities had already significantly accelerated soil erosion around lake beds on a global scale.

"We have been imprinting our presence [on] the landscape and in the natural world further back than we thought," said Nuno Carvalhais, a research group leader at the Max Planck Institute for Biogeochemistry and the senior researcher on the study published in *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/human-imprint).

The findings required an interdisciplinary approach, with different types of analyses allowing a more comprehensive picture of how human activities could be behind the accelerating erosion, Carvalhais said.

Jean-Philippe Jenny, a French geoscientist affiliated with the Max Planck Institute for Biogeochemistry and the Alpine Center for Research on Trophic Networks and Lake Ecosystems and lead author of the study, analyzed core samples of sediments collected from 632 lake beds around the world. Because sediments accumulate in lakes at continuous rates, lake sediment cores can be used as a natural archive of fluctuations in soil erosion over time.

Combining sediment rates with radioactive carbon dating data from each site, Jenny and his collaborators inferred the changes in lake sedimentation accumulation rates and found that 35% of the sampled lakes had accelerated erosion over the past 10,000 years.

The acceleration in erosion began around 4,000 years ago, and the researchers sought out the mechanisms that could explain this trend. "We built up our hypotheses, and based on these hypotheses, we [collected] the data that would either destroy or support the different hypotheses that were behind the trends," Carvalhais explained.

"We have been imprinting our presence [on] the landscape and in the natural world further back than we thought."

In the end, humans were the most likely culprit.

Changes in erosion were less related to fluctuations in precipitation and temperature, researchers found, whereas trends in deforestation coincided with the rise in erosion. Jenny and his collaborators analyzed pollen samples at each lake bed site to produce a proxy for tree coverage of the surrounding land; they found that decreases in tree cover were tightly coupled with accelerated erosion. "Deforestation at the time was caused by the human beings, because at that time they were starting to develop agriculture," said Jenny.

Humanity's Past and Future Written in the Dirt

Although soil erosion accelerated 4,000 years ago in Europe, similar trends occurred only recently in North America, probably following European immigration and importation of agricultural practices.

The research team also found that 23% of lake sites had a decrease in erosion rates, which may be the result of human-driven river management, such as the construction of dams.

"It means that we as human beings are now living in a time period where we have a huge effect on everything on the Earth, and all our activities will be recorded in the natural archives," said Jenny.

"These guys have done a really remarkably ambitious job putting the story together," said David Montgomery, a professor of Earth and space sciences at the University of Washington and author of *Dirt: The Erosion of Civilizations.* The results of the paper "put into perspective just how powerful a force people are on the planet today," he said.

Montgomery, who was not involved in the study, suggests that it was not merely deforestation that accelerated soil erosion, but subsequent agricultural activities as well. Though deforestation is a necessary first step for widespread farming, increased soil erosion is mainly driven by "the plow that followed," he said. "It wasn't simply cutting down the trees that caused the erosion; it was keeping them off the landscape through farming practices."

"What you come away with is the lesson that societies that don't take care of their soil don't last."

The erosion rates produced by conventional agricultural practices are not sustainable, and they sap crucial nutrients from the soil. "What you come away with is the lesson that societies that don't take care of their soil don't last," Montgomery said.

And there are broader environmental implications too. As with many types of large-scale human activities, increased soil erosion "can impact the climate in the long term," said Jenny.

The results of this study provide more data about "the sensitivities of the Earth system to climate and environmental factors, including humans," said Carvalhais. "And this can help us improve our ability to understand and also to predict or forecast future scenarios."

"To go into the future, we also need to understand our history," he added.

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

Geophysics Recruits Radio Telescopes

Radio telescopes reveal distant solar systems and bubbles of gas near our galaxy's center. But they're useful for more than just astronomy—a subset of the world's radio telescopes could also play an important role in geophysics research. A team of scientists has now demonstrated how radio telescopes could be linked to satellites that measure ground deformation, the first step toward studying changes in Earth's surface on a global scale.

Wanted: A Global View

"The height of Earth's surface is changing all of the time," said Amy Parker, a satellite radar specialist at Curtin University in Perth, Australia. These displacements occur for a myriad of reasons, some natural and some anthropogenic: earthquakes, mining, and groundwater extraction, for example.

But accurately monitoring these changes on intercontinental scales—important for determining how land movements affect calculations of sea level rise and fall, for instance—is currently impossible: Interferometric synthetic aperture radar (InSAR), which involves bouncing microwaves off Earth's surface and measuring their travel time and phase to trace ground deformation, works only over contiguous swaths of land, because water scatters microwaves inconsistently. InSAR is "pretty amazing," said Parker, but it measures ground displacement only relative to an arbitrary reference like the mean value in an image. It doesn't measure changes relative to an absolute reference frame, and it can't be used to study global-scale processes, said Parker. "We need to tie measurements on different continents in to a consistent reference frame."

One way of doing so, Parker and her colleagues suggest, is to connect two existing networks: InSAR satellites and radio telescopes capable of very long baseline interferometry (VLBI).

Here Come the Telescopes

Astronomical observations often involve resolving fine details, like separating two objects that appear close together in the sky. Physically larger telescopes have better angular resolution, but there's a practical limit to how large a single telescope can be.

That's where interferometry comes in. By carefully combining the light gathered by multiple telescopes linked together by precise timing, astronomers can, in a sense, build a much larger telescope: They can achieve an angular resolution equal to that of a telescope with a diameter that's the distance between the linked telescopes. Very long baseline interferometry refers to interferometry done over very large distances ("baselines"), even across continents. (Astronomers used VLBI to create the Event Horizon Telescope, a network of telescopes that obtained the first image of a black hole, revealed last April.)

When a network of VLBI telescopes accurately measures the arrival of light from a distant galaxy, researchers can compare the time stamps of the observations to determine the telescopes' positions relative to one another. Thanks to precise timing, the distances between telescopes can be measured to within a few millimeters.

A radio telescope, part of the Goldstone Deep Space Communications Complex, looms over California's Mojave Desert. Credit: NASA/JPL-Caltech

Because telescopes don't move relative to Earth's surface, these measurements reflect changes in the planet's crust and can be used to trace the motion of tectonic plates, for instance. The International VLBI Service for Geodesy and Astrometry coordinates these geodetic measurements from NASA Goddard Space Flight Center in Greenbelt, Md. Currently, there are about 40 VLBI telescopes worldwide that can do this sort of geodetic monitoring.

Tests on Two Continents

Connecting the capabilities of InSAR satellites and geodetic VLBI telescopes would open up new observing opportunities, Parker said. "We get a connection between what the satellite is measuring and the reference frame that the telescope is measuring."

To test the feasibility of this idea, the researchers focused on four geodetic VLBI telescopes, three in Australia and one in Sweden. They showed that the telescopes could be tied to the European Space Agency's Sentinel-1 satellite constellation used for InSAR by simply pointing the telescopes statically toward the location of an overpassing satellite. Microwaves emitted by the satellites were readily picked up by the telescopes and reflected back, even when the telescopes didn't track a satellite's overpass. "It's the easiest solution for an operator to implement, and it's as good as steering the telescope," said Parker.

These observations can be completed in only a minute or two, Parker and her colleagues showed, and they don't require any new instruments or infrastructure. However, it might be necessary to protect telescopes' sensitive electronics from the satellites' relatively strong signals, the researchers found. One option is to install foil—impervious to radar frequencies—around a telescope's low-noise amplifier. Another possibility, which Parker and her team tested, was to simply point the telescope slightly away from a satellite's position.

"The international network of Very Long Baseline Interferometry telescopes provides an existing, yet unexploited, link to unify satellite-radar measurements on a global scale," the researchers conclude in their study, which was published in *Geophysical Research Letters* (bit.ly/radio-telescopes).

"It's a really nice piece of work," said John Gipson, a physicist at NASA Goddard Space Flight Center and an International VLBI Service for Geodesy and Astrometry team member not involved in this research. "It's very practical."

Parker and her colleagues are optimistic that the scientific community will see the advantages of using radio telescopes for geophysics applications. They hope to see a sizable number of telescopes and InSAR satellites linked within the next year or two.

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

Opposite: Rick Bohn/U.S. Fish and Wildlife Service

What Do You Get When You Cross a Thunderstorm with a Wildfire?

Few things are more ominous than a looming thundercloud. Add a wildfire to the mix, and the result can be a towering tempest of thick smoke, smoldering embers, and superheated air.

Fire-fueled thunderstorms are naturally occurring weather systems that sometimes spin up as a result of smoke and heat billowing from intense wildfires. These extreme storms, called pyrocumulonimbus (pyroCb), occur infrequently, but when they do they can lead to tragic results.

The Making of a Firestorm

Wildfires give off intense heat, forcing large amounts of smoke and hot air to rise. As the mixture moves higher into the troposphere—the lowest layer of Earth's atmosphere—it cools and expands as the air pressure drops. Moisture in the air soon condenses, forming big puffy clouds called pyrocumulus clouds.

When conditions in the atmosphere are just right—including a hot, dry layer of air near the ground and a cooler, wetter layer above it—the atmosphere can become convectively unstable. Increasingly turbulent air sets water droplets and ice crystals in pyrocumulus clouds on a collision course, building up an electrical charge and turning the system into a towering thunderhead.

Soaring pyroCbs, which rarely produce rain on the ground even though they are thunderstorms, can even rise out of the troposphere and extend into the stratosphere tens of kilometers above Earth's surface.

Dark as Night

Not surprisingly, pyroCbs can be incredibly dangerous.

On 7 February 2009, a devastating day in Australia's history, conditions spawned at least three pyroCbs that carried embers 30 kilometers from their source and sparked lightning that ignited additional fires 100 kilometers away. Known as the Black Saturday bushfires, these fires collectively burned 4,500 square kilometers and claimed the lives of 173 people.

A pyroCb that formed during the Carr Fire near Redding, Calif., in 2018 had such strong winds that it created a tornado-strength fire vortex, and a pyroCb in Canberra, Australia, in 2003 was so extreme that it released a torrent of black hail and turned the daytime sky as dark as night.

Fortunately, these events are still relatively rare, although recent research from Australia suggests that climate change may cause conditions there to become more favorable for the formation of pyroCbs in the future.

Nick Nauslar, who forecasts fire weather for the National Oceanic and Atmospheric Administration's National Weather Service, said that about 25–50 pyroCb events occur around the world each year. He said that predicting exactly when the storms will occur remains a challenge for scientists.

"They are still really difficult to forecast," Nauslar said. Even though scientists can check the weather conditions before a fire, they can't describe exactly how a wildfire will affect the lower atmosphere and change the weather conditions. The effort to study pyroCbs "is still so young, and there's still so much to learn," Nauslar said.

Soaring pyrocumulonimbus systems can rise out of the troposphere and extend into the stratosphere tens of kilometers above Earth's surface.

Smoke High Above

A major signature of pyroCbs is their impact on the stratosphere. But until recently, scientists didn't think wildfires could inject soot, aerosols, and organic compounds high into the atmosphere.

The "idea that a firestorm could act like a volcano and inject material into the stratosphere was completely unknown," said Mike Fromm, a meteorologist at the U.S. Naval Research Laboratory in Washington, D.C. Fromm has studied pyroCbs since the late 1990s using satellite instruments.

Smoke particles from pyroCbs can stay in the atmosphere for days to weeks and, in extreme cases, months. Smoke from a massive pyroCb in Canada in 2017 remained suspended in the upper stratosphere for 8 months, according to a recent study in Science in which researchers considered the lofted pyroCb particles as a proxy to investigate the potential climatic and atmospheric effects of smoke plumes from nuclear explosions.

PyroCbs won't be causing a nuclear winter anytime soon, but Fromm told *Science News* that an open question about pyroCb plumes is whether they could damage ozone in the stratosphere. "We're still trying to understand and quantify and calculate [whether] there is, in fact, a climate impact of these plumes," Fromm told *Eos*.

Brown smoke billows from the Willow Fire in Payson, Ariz., in 2004, fueling the formation of a towering pyrocumulonimbus system above. Credit: Wikimedia Commons/Eric Neitzel, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

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

Using Garnets to Explore Arc Magma Oxidation

Ethan Baxter examines garnet samples in Sifnos, Greece. Credit: Ethan Baxter/Boston College

Researchers have long pondered why arc magmas are more oxidized than other volcanic rocks. Ethan Baxter, a geochemist at Boston College, and his colleagues recently "fingerprinted" the source of oxidizing fluids in subduction zones, bringing researchers closer to answering this question.

The research "was exciting because it was conducted by a master's student, and it brought together a large, collaborative [international] group" of researchers from different specialties, Baxter said, referring to Anna Gerrits, whose research interests sparked the investigation.

For three zoned garnet crystals from Sifnos, Greece, researchers measured the oxygen fugacity (which they describe as a thermodynamic property serving as a chemical control in subduction zones and other environments) and stable iron isotope composition. It's the first study to examine "zonation of iron isotopes from garnet crystals in a subduction zone," Baxter said.

The study concludes that the garnets and the surrounding mineral assemblage display "a record of progressive dehydration," including lawsonite dehydration. Garnet interiors grew under relatively oxidized conditions, the researchers said, whereas the rims record reduced conditions. These findings support an existing hypothesis that sulfate or other oxidizing species released during dehydration of subducting lithologies contribute to oxidation of the mantle wedge above subduction zones.

"It's a careful study, with a tantalizing result," said Katherine Kelley, a professor of oceanography at the University of Rhode Island. "Metamorphic rocks can be incredibly complex, so when a study reaches in and draws out a simple result, it can be incredibly revealing."

"Metamorphic rocks can be incredibly complex, so when a study reaches in and draws out a simple result, it can be incredibly revealing."

Greek Crystals

The garnet crystals came from a suite of subduction zone samples that were previously collected from Sifnos, Baxter said. About 45 million years ago, the area was rich with volcanic explosions triggered by geological activity.

Although the three crystals under study share a similar subduction history, their compositions and redox records are varied, Baxter noted. Two of the rocks show systemic changes in iron isotope compositions, indicating that they were still growing while lawsonite breakdown occurred. However, those changes aren't present in the third rock, demonstrating that it stopped growing before any major release of water occurred. The absence of these changes in the third sample clued the team in to the conditions responsible for the release of oxidizing fluids in subduction zones.

"The method these authors used, to extract the individual growth zones of a single crystal and perform isotopic analysis on [it], is a novel approach that will ultimately tell us even more about the conditions [occurring] during metamorphism of these types of rocks at depth.... This opens up many new doors to discovery of the metamorphic processes in the subducting plate," Kelley said.

Because the results of this study are based on the study of three rocks collected from one island, Baxter said, the team wants to analyze rocks collected from other field sites, such as the Italian Alps, to look for global trends applying to subduction zones. The team also wants to delve into why fluids released in subduction zones are oxidized and "the chemistry responsible for creating that oxidizing fluid," he said.

The researchers reported their results in a *Nature Geoscience* paper (bit.ly/oxidizing-fluids).

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

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Beavers: Nature's "Little Firefighters"

When a wildfire tears through a landscape, there can be little left behind.

A new study, though, suggests that beavers may be protecting life around streams, thanks to their signature dams. Satellite images from five major wildfires in the United States revealed that corridors around beaver habitat stayed green even after a wildfire.

Millions of beavers live in forests across North America, and they make their homes in a particular way. By stacking piles of branches and rocks in a river's path, they slow its flow and create a pool of calm water to call home. They even dig little channels radiating out from their pools to create "little water highways," said Emily Fairfax, an assistant professor at California State University Channel Islands who led the study.

Fairfax wondered whether beaver dams would insulate riparian vegetation, as well as the fish and amphibians that live there, from wildfire damage. Wildfires course through landscapes naturally, but blazes will become more frequent as climate change dries out forests.

Fairfax sifted through records of past fires in the U.S. Geological Survey's database and chose five recent fires that occurred in beaver habitat. She then analyzed the "greenness" of vegetation before, during, and after the fires. She used measurements from NASA's Landsat satellites, which use red and near-infrared light to detect the lushness of vegetation.

This screenshot from a stop-animation video created by Emily Fairfax shows how beaver dams can insulate surrounding vegetation from wildfires. See link at the end of the article to watch the video.

Fairfax found that vegetation along sections of a river without dams burned straight to the river's edge. But for sections with a resident beaver, "essentially, the plants don't know a fire is happening." The channels dug by beavers acted like irrigation channels, said Fairfax, keeping vegetation too wet to burn, even during drought. In all, stretches of river without beavers lost 51% of their vegetation greenness, compared with a 19% reduction for sections with beavers.

Joseph Wagenbrenner, a research hydrologist at the U.S. Forest Service who was not involved with the research, said that protecting the vegetation around rivers can help prevent problems downstream. Contaminants and sediment can clog rivers right after a fire, degrading water quality and threatening life. He said the work could be important for scientists' efforts to reduce wildfire's negative impacts.

Fairfax presented the research at AGU's Fall Meeting 2019 in San Francisco, Calif. (bit.ly/smokey-the-beaver). She also created a stop-animation story of one little beaver's influence during a burn, which you can watch online at bit.ly/natures-firefighters.

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

Creating Spaces for Geoscientists with Disabilities to Thrive

Nearly a quarter of the U.S. population has some form of disability. In the geosciences, when we fail to account for the policies and cultures that isolate and exclude people with disabilities, we continue to send the message to more than 20% of the population that geoscience careers may not be a welcoming place for them. We need to become more aware of the challenges that people with disabilities face within the geosciences and work to dismantle those barriers in our classrooms, research groups, departments, and the scientific community at large. Disability presents across all demographics, making it an important yet still often overlooked piece of the diversity puzzle. Creating a better path for participation for disabled geoscientists will open opportunities across all underrepresented groups.

Participants in an accessible geology field trip with the International Association for Geoscience Diversity in 2016 look over the South Rim of the Grand Canyon in Arizona. In the foreground are Jen Piatek (left) and coauthor Sean Thatcher; in the middle distance (left to right) are Grant Vincent, Anna Todd, and Matt O'Brien; and on the ledge are Amanda Haddock (left) and Will Kilpack. Credit: Anita Marshall

Access for All Versus Cost and Sentimentality

"Of course our building is accessible—there is only one small step to get inside."

Physical barriers to participation in geoscience activities exist everywhere [*Carabajal et al.,* 2017]. Buildings on campus may include inaccessible laboratories and restrooms, hidden or out-of-the-way ramps, and freight elevators that look like something from a horror movie. These issues are often more common in geoscience departments, which tend to be located in some of the oldest buildings on campus and thus are often exempt from accessibility requirements under the Americans with Disabilities Act.

Although physical accessibility improvements can be costly and in some cases nearly impossible to fully address, we can make ourselves aware of the numerous barriers in our physical spaces and advocate for changes that can be made. Sometimes access can be greatly improved with small adjustments, such as using wooden blocks to raise table heights or inexpensive transition strips on doorways with high thresholds. The National Park Service, which manages numerous historically significant locations in the United States, recognized that in leaving spaces unmodified simply because it was not legally obligated to improve them, it was "losing the opportunity to reach the widest possible audience and share a spectrum of experiences" [*Jester and Park,* 1993]. It has invested significant resources into improving access and usability of indoor and outdoor spaces in a way that blends into the style of historic properties. For example, the recently completed ramp at the Rainbow Forest Museum at Petrified Forest National Park in Arizona brings wheelchair access to the main entrance rather than to the back door, an important affective change that blends seamlessly with the 1930s architecture.

Decision-makers need to involve the people whom the changes would most benefit. This collaboration is also a good way to build community, so long as the burden is not put on the disabled to do the bulk of the advocacy work themselves. The important thing at the departmental level is to demonstrate a solutions-oriented mind-set and a willingness to prioritize inclusion over sentimental desires to keep physical spaces unaltered.

Sometimes access can be greatly improved with small adjustments, such as using wooden blocks to raise table heights or inexpensive transition strips on doorways with high thresholds.

Flexible Fieldwork

"Sorry, but you can't come on the research trip—you'd be a liability in the field."

Students with disabilities are often prevented from completing their degree because of the lack of fieldwork opportunities. Many accessibility challenges in field-based learning result not from the physical barriers of the terrain or the task but from needlessly inflexible policies that restrict a student's participation. Examples include deaf and hard of hearing students being told they are liabilities because they won't be able to hear the instructors or potential hazards, and wheelchair users being told that departmental policies bar them from driving their own vehicles. Yet at the same time, departments claim that budgetary reasons prohibit them from providing accessible vans or sign language interpreters. Instead, these students are sent off on independent assignments, which are often less rigorous and far less effective for academic growth and limit the development of the social bonds that promote future success in the discipline [*Streule and Craig*, 2016; *Atchison et al.*, 2019].

If field experiences are integral to professional preparation, then they must be made equitable for all students. There are a small number of programs with inclusive field opportunities for students with disabilities, such as the University of Arizona's Accessible Earth program and the Enabling Remote Activity (ERA) project at the Open University. Building on the technology-based approach of the ERA project, the University of Florida is developing a lending library of tech tools to improve accessibility of existing field courses.

A single instructor's actions can be the point on which a student determines his or her sense of belonging, or lack thereof, in the entire discipline.

Some geoscience programs are developing alternatives to on-location fieldwork, such as the University of Leeds's Virtual Landscapes and Western Washington University's Lab Camp.

Approaching Accommodations as Support, Not a Free Pass

"Your exams must be so much easier with accommodations!"

Accommodations—modifications specified by on-campus disability services to enable equitable treatment—are often the first test of a department's culture. Despite legal mandates, instances of instructors withholding accommodations or making the process overly difficult continue to occur. Some students formally push back by filing complaints, but most choose to exit these situations by dropping the course in question or changing degree tracks entirely, leaving no evidence as to why they left.

On the other hand, faculty who demonstrate an awareness of the importance of accommodations cultivate a sense of trust that enables students to focus on learning rather than on the need to self-advocate. A recent study showed that upon completion of accessibility and inclusion training for geoscience teaching assistants, the number of students approaching instructors with accessibility requests increased, as did the number of students feeling that their instructor had a genuine interest in their success [*Fairfax and Brown*, 2019]. A single instructor's actions can be the point on which a student determines his or her sense of belonging, or lack thereof, in the entire discipline.

Recruitment: Proving You Want the Best, Not the Easiest

"Why would a disabled person even want a geology degree? They won't get a job with it."

The need for disability-inclusive practices extends into the professional sphere, where geoscience employers may hold significant biases against candidates with disabilities, despite the fact that people with all types of disabilities have had and continue to have successful careers in the geosciences [*Atchison and Libarkin*, 2016]. Nearly all of the burden for addressing disability in the professional sphere falls to the disabled person. During the job hunt, candidates with disabilities must determine how best to handle hiring committees who are not trained in equitable interview procedures. Once hired, employees with disabilities must constantly consider the balance of personal needs versus cultural stigma when asking for accommodations.

Departments should seek to address this by putting the burden of providing a safe and stable workplace back onto the employer. This effort can start with more inclusive job descriptions, by providing evidence up front that more effort has been given to equitable treatment beyond copying and pasting the university's diversity and accommodation statement, and by demonstrating that institution-wide support structures are in place to enable students' success.

The academic institution may not have purview over some accommodation barriers, but it can still provide guidance that leads to the best chances of success for its students. For example, government-run disability services often vary from state to state, which may greatly affect students' decisions about which graduate or postdoctoral program they're able to attend. Medical care and transportation are typically limited to a small geographic area, so individuals relying upon these services as their primary means of transportation are greatly hindered in participating in such extracurricular activities as field trips and professional development opportunities.

In addition, residency requirements and other bureaucratic hurdles may require a person who needs support services to relocate well before financial compensation begins—a gap that for many is simply not feasible. Academic institutions may not be able to change or eliminate these state-level obstacles, but they can certainly provide the best information to their students about what to expect and explore ways to make this transition less of a financial barrier.

Disrupting an Exclusionary Culture

"Do you think you could finish this program with your…limitations?"

Many students declare geoscience majors after taking required college courses or through other outreach events, but disability is rarely considered in the design of such introductory course materials or recruitment activities. As a result, everything from how we advertise our programs (typically to attract adventurous, outdoorsy students) to the lack of disability representation in geoscience course material and a cultural acceptance of condescending comments directed at those who do show an interest sends the message that people with disabilities need not apply [*Bush and Mattox*, 2019; *Hall et al.*, 2004].

What we say and do when we assume there are no people with disabilities present can perpetuate an exclusive culture.

This message is amplified for people from underrepresented groups who also have a disability. Countering these recruitment barriers requires critically evaluating how we are promoting our departments through advertisements and social media, presenting a more balanced view of the many fields of study and career paths available within the geosciences, and acknowledging that scientists with disabilities already work within our discipline [*Sexton et al.*, 2014; *Mol and Atchison*, 2019].

Finally, the geoscience community can suffer from the same casual ableism—beliefs

The access ramp leading up to the front entrance to the Rainbow Forest Museum at the Petrified Forest National Park was made with natural sandstone to match the original 1931 building. Credit: NPS/Hallie Larsen

or practices that discriminate against people with disabilities—that the rest of society does. Comments that may seem complimentary may, in fact, reinforce a feeling of "otherness." Most ableist comments can be avoided simply by considering whether the same comment would be made to a person who doesn't have a disability.

More insidious than overt barriers, cultural ableism comes in the form of well-meaning but uninformed viewpoints that erase or blame people with disabilities for societal problems, such as recent efforts to ban plastic straws. Despite being well intended from an environmental perspective, the public shaming of people using straws can be extremely upsetting for a person with a disability who is studying in an environmentally focused discipline and also needs to use plastic straws to live. Exclusive cultures develop when there is a lack of diverse perspectives.

Don't Wait Until the Need Arises

Truly inclusive cultures are proactive about creating environments that are welcoming to everyone before an immediate need arises. What we say and do when we assume there are no people with disabilities present can perpetuate an exclusive culture—to the person in the room with a nonapparent disability or to the person who becomes disabled later in life [see, e.g., *Marshall*, 2018]. Inclusive cultures recognize the benefits of diversity and see inclusion not as a burden but as something inherently beneficial.

As AGU celebrates 100 years of scientific innovation, we have a unique opportunity to think critically about the culture of the geosciences. We should examine the exclusionary nature of our past and apply what we've learned to build a more inclusive future that recognizes the value of diversity and actively works to break down the barriers to participation. These challenges require a collective will, but in a community that can respond to the challenges of studying deep-sea trenches, Earth's interior, and the far reaches of outerspace, we are entirely capable of meeting the challenges of accessibility and creating innovative and inclusive scientific environments in which everyone can thrive.

Resources

Resources for accessibility and inclusion training are available from the Supporting and Advancing Geoscience Education at Two-Year Colleges (SAGE 2YC) program, the Center for Universal Design in Education, and the International Association for Geoscience Diversity. Many universities also offer training through their disability resource centers.

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This article is part of a series produced in collaboration with AGU's Diversity and Inclusion Advisory Committee to highlight perspectives from underrepresented communities in the geosciences. Read the entire series at bit.ly/Eos-diversity.

Improving Reproducibility in Earth Science Research

Software-based workflow management systems that incorporate standards from the Earth science community can facilitate the assessment of repeatability, replicability, and reproducibility of scientific claims and bridge current and future computing environments. Credit: geralt, Pixabay License

A cornerstone of solid science is the ability of scientists to assess the correctness of other researchers' results and conclusions, critically and without restrictions [see *Plesser,* 2018; *National Academies of Sciences, Engineering, and Medicine,* 2019]. Three common practices for such assessments, often called the 3Rs, range in difficulty from low to high [*Association for Computing Machinery,* 2016]:

- repeatability (same team, same experimental setup)
- replicability (different team, same experimental setup)
- reproducibility (different team, different experimental setup)

Much of Earth science today is computationally heavy, involving the use of specialized algorithms, software, and computing environments. Reproducing such science requires that not only the software but also the associated data and information about the computing environment that generated the original results be available to other researchers. In reality, this is difficult for a number of reasons. Here we discuss these challenges and address how new software technology could better facilitate scientific reproducibility in Earth science.

Mapping the Path from Data to Results

Scientific investigations usually follow a workflow, a sequence of steps through which data are processed and analyzed to give an end result, or product. Examples of Earth science workflows include relatively straightforward analyses of sea surface temperatures to sophisticated numerical modeling of weather and climate. Numerous computer programs and software packages have been developed to support scientific research workflows and their applications in Earth science. For example, complex computer software uses data from spaceborne sensors and other Earth observations to retrieve environmental parameters such as precipitation and hydrometeor (liquid or solid water particle) profiles.

Access to input data is fundamentally important for reproducibility. When a scientist or a journal reviewer tries to reproduce someone else's results, it can be challenging to locate the data used, especially if the research was not done recently.

Although publishers increasingly require authors to include source information for the data used in their research (e.g., web links of last access and digital object identifiers (DOIs)), problems remain. Because many Earth science disciplines generate data sets with different formats, data structures, and file stitching or aggregation methods, data sets quoted from web links or DOIs may not be immediately usable, instead requiring preprocessing that involves a lot of work and technical expertise. But reviewers are volunteers who seldom have much time to spend on data processing, especially if input data sets are large.

Reproducing research results also requires that any software used in generating the results be available to other scientists. This is not always the case, however. And even when it is available, missing information or incomplete descriptions can make the software hard to understand.

The workflow embedded in software must be well described for others to understand how it processes data. This description includes input and output data sets, workflow logic, algorithms used, the version of the software or library used, and more.

But researchers are under immense pressure to publish their work and do not always have time to devote to documenting or training outside researchers in their programs and processes. Furthermore, software packages are often written by students, postdocs, or interns, who may not be available to provide continuing support for their software after they complete their studies and move on to other institutions. So researchers seeking to reproduce results generated using custom-built software often find that support services are not available to answer questions.

Another major cause of missing software or incomplete documentation is that scientific publishers generally do not require that authors submit and publish custom software or code they used in their work. Therefore, scientists have very little incentive for doing the extra work to make the software publicly available. On the other hand, even if a scientist submits software to a publisher along with a research paper [e.g., *Science,* 2019], in practical terms it is still very difficult for reviewers to retrieve input data and understand and successfully run the software in their own computing environment.

Supporting Legacy Data and Computing Environments

For older research papers, data access problems are even bigger. Who will ensure that the data and software used in these papers are still available for reproducibility after a number of years? Data DOIs are used in some research papers to reference the data involved, but eventually, it is the responsibility of data archive centers to uninterruptedly maintain data and services.

For example, there can be multiple versions of satellite-based data products because algorithms evolve and are improved over time. A common practice for data archive centers is to keep only the latest version of a data product, which can make accessing data sets in earlier versions very difficult, especially for products derived from raw measurement data.

Scientists seeking to assess or verify results in old publications face an even more difficult challenge. In theory, scientific data processing centers or principal investigators can reproduce these old-version data products using algorithms with raw measurement data. In reality, limited resources and limited demand for legacy data products compared with demand for the newest version make this a difficult task. Thus, it is necessary to archive both raw and derived data sets in all versions because previously published research papers are linked to these data sets.

In addition to software and data, scientific reproducibility requires knowledge of and access to the required computing environment. This environment includes the appropriate computer operating system (in the version used to generate the original output), sufficient data storage resources, adequate computing power, and the necessary software libraries (which can be outdated or missing entirely). Scientists often find that the computing environment they have cannot support software from the third party that generated the data product.

Compounding these problems are the security risks associated with running third-party software, even software provided by fellow scientists, that can impose threats unknowingly. These risks can be dangerously high, making scientists reluctant to run third-party software.

Access to input data is fundamentally important for reproducibility.

Updating Software Technology

Can software technology help remove barriers to reproducibility in the Earth sciences, given the many complicated requirements for reproducibility? Earth scientists, who are often not computer experts, need a software-based workflow management system to keep all the related elements organized. Such a system can liberate them from tedious computer hardware and software tasks and allow them to focus more on science issues [*Claerbout and Karrenbach,* 1992; *Donoho et al.,* 2009; *Peng,* 2011].

Workflow management software is important for efficiently and successfully implementing the 3Rs. A management system should be able to track the progress of each workflow automatically and record detailed information about the data, software, and computing environment. The system should also record and track all activities involved in each step of scientific processing, such as data inputs and outputs, data analysis, and visualization. Recorded provenance information can be attached with journal paper submissions so that peer reviewers or other colleagues can examine the details and run the workflow independently.

The workflow management system must be user friendly to minimize the learning curve and maximize its usefulness in 3R activities. The system must also enable scientists to conduct collaborative work more efficiently in different communities by making reproducibility not only possible but also simple.

Such a system benefits data archive centers as well because the centers can record and provide provenance information for their archived data sets. Scientists who download data from these centers can then pass this information along and add it to new workflows.

Enabling the 3Rs

Several workflow management systems already exist [e.g., *Kepler,* 2019] that allow scientists to add different analytical methods and to record the workflow provenance. However, these systems still have many limitations. We argue that it is critical to remove these obstacles and simplify the process for implementing the 3Rs.

Currently, for example, provenance information may not be interoperable from one workflow system to another, and there may not be sufficient provenance information available to perform the 3Rs [e.g., *World Wide Web Consortium,* 2013]. Therefore, Earth science community stakeholders need to develop 3R standards. Furthermore, most existing systems require users to have expertise in computer science to add analytical algorithms into a workflow, but most Earth scientists do not currently have the requisite level of expertise.

We envision that future computing in Earth science will occur in an integrated environment, most likely based on cloud computing. In such an environment, scientists can run software and do data analysis "close to the data" using the same shared resources rather than downloading data sets to their own computing environments. In such an environment, standard provenance information will be automatically recorded for each run.

However, until this happens, we need to bridge current and future software practices. For example, to better document their research, scientists need workflow systems that can automatically generate provenance information based on community-defined standards. A scientist could then export the standardized and human-readable provenance information to their paper for journal submission. The system, meanwhile, could also assemble the software code, input data information, and other information into a virtual package like a Docker image so the package could be deployed seamlessly by other scientists.

There are many challenges in enabling repeatability, replicability, and reproducibility in Earth science. To overcome these challenges, it is necessary to develop software management systems with community-based standards to bridge current and future computing environments. New mandatory requirements from stakeholders will likely play an important role in accelerating the development of such systems and community-based standards. These systems, especially if they prove user-friendly, will help facilitate the 3Rs.

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Smoke plumes spread west from the Camp Fire in Northern California and the Hill and Woolsey Fires in Southern California on 9 November 2018, as seen in this image captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. Smaller plumes from other fires in central California are also visible. Credit: NASA Earth Observatory image by Joshua Stevens, using MODIS data from NASA EOSDIS/LANCE and GIBS/Worldview

A Global Perspective on Wildfires

Satellites provide global-scale data that are invaluable in efforts to understand, monitor, and respond to wildfires and emissions, which are increasingly affecting climate and putting humans at risk.

By Ralph Kahn

Fire is part of the natural ecology of most vegetated settings, but wildland fire is also a major—and increasing—hazard in many populated regions of the world, to which recent severe fires in Australia, California, Indonesia, South America, and elsewhere attest. Aggressive fire suppression policies during much of the 20th century have allowed fuel loads to grow artificially heavy, while settlements and agricultural enterprises progressively encroach on formerly pristine habitats. More broadly, shifting patterns of precipitation, lightning occurrence, and temperature in a changing climate are creating conditions that favor increasingly frequent and intense biomass burning, in ecosystems from boreal peatlands to tropical rain forests.

Operating from the ground, from observation towers, and from aircraft, fire response teams struggle to identify nascent ignitions over vast wilderness areas, to map active fire fronts and locate hot spots, and to track the dispersion of smoke plumes that can affect air quality hundreds of kilometers downwind of sources.

Remote sensing instruments are relatively blunt objects for characterizing wildfires and their impacts, compared with traditional in situ monitoring. However, they offer the advantage of providing frequent, broad coverage at minimal incremental cost and at no risk to observers. Over the past 20 years, the research community has developed tools and techniques to capture key aspects of fire behavior and impacts, with data from spaceborne instruments such as the Moderate Resolution Imaging Spectroradiometers (MODIS) aboard NASA's Terra and Aqua satellites and the Multiangle Imaging Spectroradiometer (MISR) aboard Terra. This article reviews selected contributions that satellite instruments are making to advance our understanding and monitoring of, as well as our responses to, wildfires globally.

Fire Detection

Fire detection and fire front mapping are fundamental applications related to wildland fire with which satellite remote sensing can help. They rely on identifying bright anomalies in satellite-detected infrared radiance relative to background and are quantified with a measure called Fire Radiative Power (FRP), assessed at a wavelength of about 4 micrometers [e.g., *Giglio et al.,* 2016].

The MODIS instruments, as well as the National Oceanic and Atmospheric Administration's (NOAA) Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership and NOAA-20 satellites, all obtain twice-daily, near-global measurements used to determine FRP, with a fire pixel resolution of up to about 0.5–1 kilometer at nadir (directly below the satellite). The Advanced Baseline Imagers on NOAA's Geostationary Operational Environmental Satellite (GOES)-16 and GOES-17 platforms (and on earlier NOAA geostationary satellites) perform fire detection much more frequently [e.g., *Zhang et al.,* 2012] but at a lower resolution of no better than 2 kilometers at nadir.

With these single-view, multispectral imagers, spatial resolution diminishes and atmospheric opacity increases away from the nadir, so many agricultural fires and other fires smaller than pixel resolution go undetected. However, the satellite data offer global coverage and can be automatically processed, enabling rapid response. Many imagers can also detect burn scars, which sometimes reveal the location and extent of smaller fires after the fact [*Randerson et al.,* 2012].

Remote sensing instruments are relatively blunt objects for characterizing wildfires. However, they offer the advantage of providing frequent, broad coverage at minimal incremental cost and at no risk to observers.

Smoke Injection Height

Smoke tends to stay aloft longer, travel farther, and have a wider environmental impact if it rises above the near-surface planetary boundary layer (which is typically up to a few kilometers thick but depends on location and varies diurnally). Injection height and source strength are the critical parameters representing aerosol sources in climate and air quality models. Satellites are providing observational constraints on both these quantities.

Approximations of smoke injection height can be modeled based on the dynamical heat flux at the surface, the atmospheric stability structure, and the entrainment of ambient atmosphere into the rising plume. Combining FRP with representations of atmospheric structure from numerical weather models and simplified parameterizations of entrainment yields reasonable estimates of injection heights in many circumstances [e.g., *Paugam et al.,* 2016]. Various factors introduce uncertainties, however, such as the coarse resolution at which FRP can be determined relative to the size of typical active burning areas, differences between the radiation emitted by flaming versus smoldering fires, and the sometimes substantial opacity of overlying smoke at relevant wavelengths [*Kahn et al.,* 2008].

An alternative approach for determining injection heights involves using multiangle imaging to directly measure the parallax associated with smoke plume features identified as contrast patterns among adjacent pixels [e.g., *Kahn et al.,* 2007]. The MISR instrument uses nine cameras pointed in the along-track direction that view at different angles ahead of, beneath, and behind the Terra satellite. As the satellite orbits Earth approximately pole to pole, these cameras sweep out a roughly 400-kilometer-wide swath in each of four spectral bands [*Diner et al.,* 2005]. Spatial resolution is between 275 meters and 1.1 kilometers, depending on channel.

With such data, both smoke plume elevation and associated wind vectors can be derived geometrically, provided that contrast elements in the plume can be identified in multiple views (usually true near-source). The accuracy of heights retrieved with this technique is between 250 and 500 meters, except when wind vectors are aligned along-track, in which case small errors in wind direction can produce larger uncertainties. These retrievals cannot capture the very tops and bottoms of smoke plumes, but the distribution of retrieved heights gives an indication of a plume's vertical extent.

Specialized software allows for plume height retrievals on a case-by-case basis with MISR data [*Nelson et al.,* 2013]. Figure 1 provides an example of this capability for the Camp Fire, which burned roughly 620 square kilometers of Northern California in November 2018 in what became the state's most destructive and deadly fire. As seen in Figures 1b and 1c, the plume reached its highest altitude, about 5 kilometers, near the source of the fire.

The main limitations of this technique are MISR's relatively narrow swath, which provides global coverage only about once per week, and the roughly 10:30 a.m. equator-crossing time, which precludes observing diurnal fire variation and misses the typical afternoon peak in fire activity. Nevertheless, enough data have been collected during MISR's 20 years in orbit to create a global climatology of representative plume heights, stratified by geographic region, biome, and season [*Val Martin et al.,* 2018].

Recently, a technique to derive near-source plume layer heights using MODIS thermal infrared data was introduced [*Lyapustin et al.,* 2019]. This approach entails more assumptions than the MISR geometric retrieval and, as with MISR, requires sufficient plume opacity to obtain a useful signal. Researchers have also explored using data from the Tropospheric Monitoring Instrument (TROPOMI) aboard the European Space Agency's Sentinel-5 Precursor satellite for mapping plume layer heights (D. Griffin et al., The 2018 fire season in North America as seen by TROPOMI: Aerosol layer height validation and evaluation of model-derived plume heights, submitted to *Atmospheric Measurement Techniques,* 2019). MODIS and TROPOMI have much wider swaths than MISR, and the MODIS technique works at night as well as during daytime, so these methods offer the possibility of more frequent, global coverage.

Smoke Source Strength

Because FRP contains information about fire intensity, it has been used to estimate smoke source strength. One advanced approach divides the plume aerosol optical depth (AOD; a measure of atmospheric opacity caused by aerosols, also derived from MODIS) by the age of a plume, as derived from the plume's horizontal extent in MODIS imagery and advection speed from a reanalysis model, to obtain a factor related to the smoke emission rate [*Ichoku and Ellison,* 2014]. The relationship between this factor and the FRP, evaluated over multiple cases, provides an ecosystem-specific emission coefficient that when multiplied by the FRP for an individual fire, yields an estimated source strength.

Other approaches rely on combining satellite-retrieved smoke plume opacities with a chemical transport model. The model is run either backward, starting with satellite-retrieved AODs over a wide area to derive source locations and emission intensities [e.g., *Dubovik et al.,* 2008], or forward, starting with the known fire locations, initializing the model with various smoke source strengths, and comparing model-simulated AODs with data retrieved from space [*Petrenko et al.,* 2017]. Better constraints on the assumptions in these models are required for many applications, such as climate prediction, and will also advance our ability to estimate smoke source strength with these methods for air quality forecasting [e.g., *Li et al.,* 2019].

Smoke Plume Transport and Evolution

Because of gaps in satellite spatial and temporal coverage and ambiguities in determining aerosol type, chemical transport models, which represent particle dispersion, physical and chemical transformation, and deposition processes, play a central role in mapping the downwind evolution of smoke plumes. Yet satellites offer observations that are essential for constraining and validating model simulations of transports [e.g., *Ichoku et al.,* 2012].

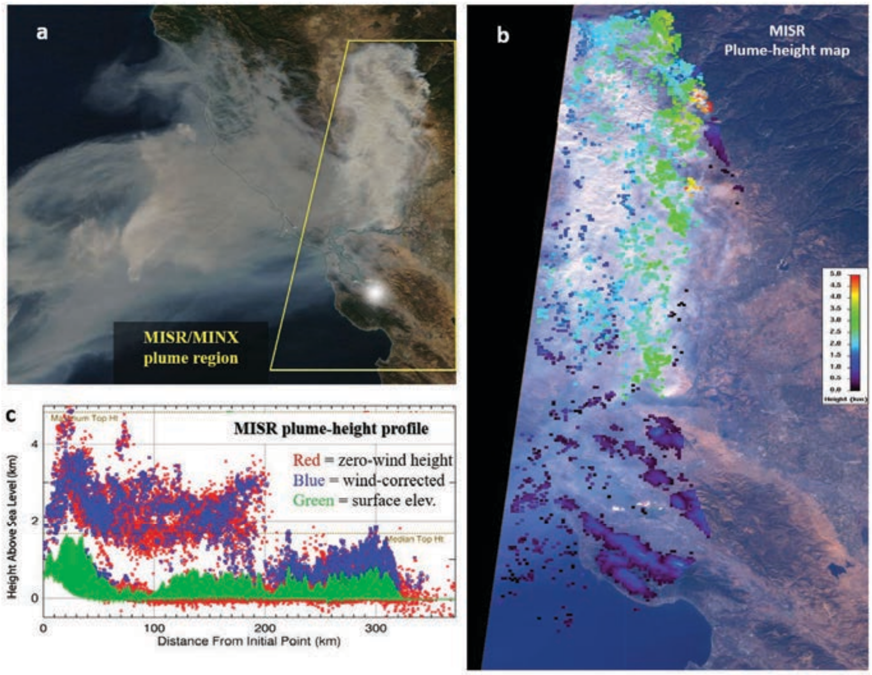

Fig. 1. The Camp Fire, which burned roughly 620 square kilometers of Northern California in November 2018, is the most destructive and deadly fire in the state's history. (a) Terra/MODIS context image showing the fire plume on 9 November 2018. The region shown in Figure 1b is outlined in yellow. (b) Plume height retrievals were generated with the Multiangle Imaging Spectroradiometer (MISR) Interactive Explorer (MINX) software. (c) MISR/MINX plume height profile, displayed as a function of distance from the source for both zero-wind (red) and wind-corrected (blue) plume elevation. Plume injection height determines how long smoke will stay aloft, how far it travels, and, generally, its environmental impact. Credit: V. Flower and R. Kahn, NASA Goddard Space Flight Center

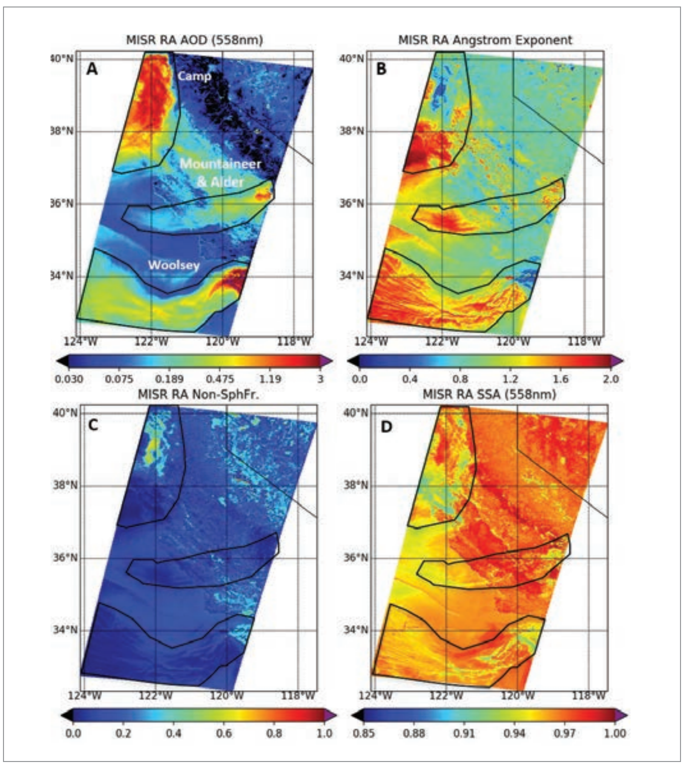

Fig. 2. This image sequence shows various smoke particle properties on 9 November 2018 from the Camp Fire in Northern California, the Mountaineer and Alder Fires in east central California, and the Woolsey Fire in Southern California, retrieved using the MISR Research Aerosol (RA) algorithm. (a) Aerosol optical depth (AOD) at 558 nanometers, with the plumes of the three fire groups outlined and labeled. (b) Ångström exponent (ANG), a rough proxy for effective particle size. (Larger ANGs indicate smaller effective particle size.) (c) Aerosol optical depth (AOD) fraction from nonspherical particles. (d) Retrieved particle single-scattering albedo (SSA) map at 558 nanometers. Note that particles in the north central part of the Camp Fire plume are distinctly larger (smaller ANG), brighter (larger SSA), and more nonspherical than the rest of the plume. These particles correspond to smoke from the town of Paradise, Calif., whereas the surrounding smoke was generated by burning vegetation. Smoke particle properties help with source attribution and provide clues to the physical and chemical mechanisms operating as smoke plumes evolve. Credit: V. Flower, R. Kahn, and J. Limbacher, NASA Goddard Space Flight Center

Scientists map aerosol plumes during transport—sometimes hundreds or even thousands of kilometers from sources—using imagery from broad-swath, single-view imagers such as MODIS and VIIRS. Instruments such as the Atmospheric Infrared Sounder aboard Aqua and the Measurement of Pollution in the Troposphere sensor aboard Terra also track transport and dispersion of gases like carbon monoxide from fires [e.g., *Witte et al.,* 2011; *Liu et al.,* 2005]. Downwind plume elevation is often captured by the space-based lidar aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. CALIPSO data are complemetary to MISR plume height retrievals, as MISR provides much greater coverage but can obtain results only from near-source, whereas CALIPSO can sample diffuse but much more extensive smoke layers downwind [*Kahn et al.,* 2008].

Multiangle, multispectral MISR data also provide qualitative constraints on aerosol microphysical properties, including particle size, spectral light absorption, and shape [*Kahn and Gaitley,* 2015]. Such information offers clues to the physical and chemical mechanisms operating as smoke plumes evolve. Retrievals of these particle properties depend on smoke plumes having sufficiently high AOD, which is usually not a problem near smoke sources.

A research version of the MISR aerosol algorithm, running on a case-by-case basis, is optimized for these retrievals [e.g., *Limbacher and Kahn,* 2014]. Observations from this algorithm are useful in identifying processes such as size-selective or size-independent particle deposition, particle oxidation and/or hydration, particle aggregation, and new particle formation. Such analysis has recently been applied to volcanic as well as smoke plumes [e.g., *Flower and Kahn,* 2020].

Figure 2 shows MISR research algorithm results for four major California fires burning on 9 November 2018. Note that for the Camp Fire, smoke generated by burning in the town of Paradise (in the north central portion of the outlined plume) contains distinctly larger, brighter, and more nonspherical particles than smoke generated from the surrounding vegetation.

Implications and Future Prospects

Among the first results from the emerging global picture of wildland fires provided by satellites is that up to about 20% of satellite-detected fires in North America inject smoke above the planetary boundary layer and that generally, boreal forest fires produce the largest fraction of elevated smoke plumes, whereas agricultural fires tend to inject smoke only within the boundary layer [e.g., *Val Martin et al.,* 2010]. Under favorable meteorological conditions, including moist atmospheric layers concentrated in the midtroposphere [*Peterson et al.,* 2017], pyrocumulonimbus have also been identified in the satellite data [e.g., *Fromm et al.,* 2010]. These extreme fire-driven weather phenomena can inject smoke into the lower stratosphere, where it might remain for several months, traversing the globe and possibly having climate impacts comparable to those of injections from moderate volcanic eruptions [*Peterson et al.,* 2018].

Using regional-scale, multiyear satellite data detailing smoke amount, particle type, and dispersion, patterns relating plume properties to vegetation types have been examined for Indonesia [*Tosca et al.,* 2011], peatlands in the Maritime Continent of Southeast Asia [*Lee et al.,* 2018], and multiple Amazon ecosystems [*Gonzalez-Alonso et al.,* 2019]. Conditions producing different proportions of black and brown carbon particles, and their evolution downwind, are being assessed. Relationships between smoke and cloud properties are also beginning to provide constraints on aerosol-cloud interactions [e.g., *Tosca et al.,* 2014].

With recent advances in imagers on geostationary platforms, limitations on satellite diurnal coverage of fires are being reduced. Space-based infrared hot spot detection from broad-swath imagers and smoke injection heights from multiangle imagers have been used experimentally to locate fires and forecast air quality hazards in emergency response situations [e.g., *Solomos et al.*, 2015]. And initial efforts are being made to constrain climate models with satellite-derived smoke source strength and injection height data.

These applications represent early steps toward realizing the many contributions that satellite products can make toward understanding and responding to wildfire environmental impacts on both short and long timescales. As techniques for extracting information about wildfires and their smoke plumes are refined further, future spacecraft instruments, possibly in combination with smallsats and drones, can be designed to optimize data for these applications.

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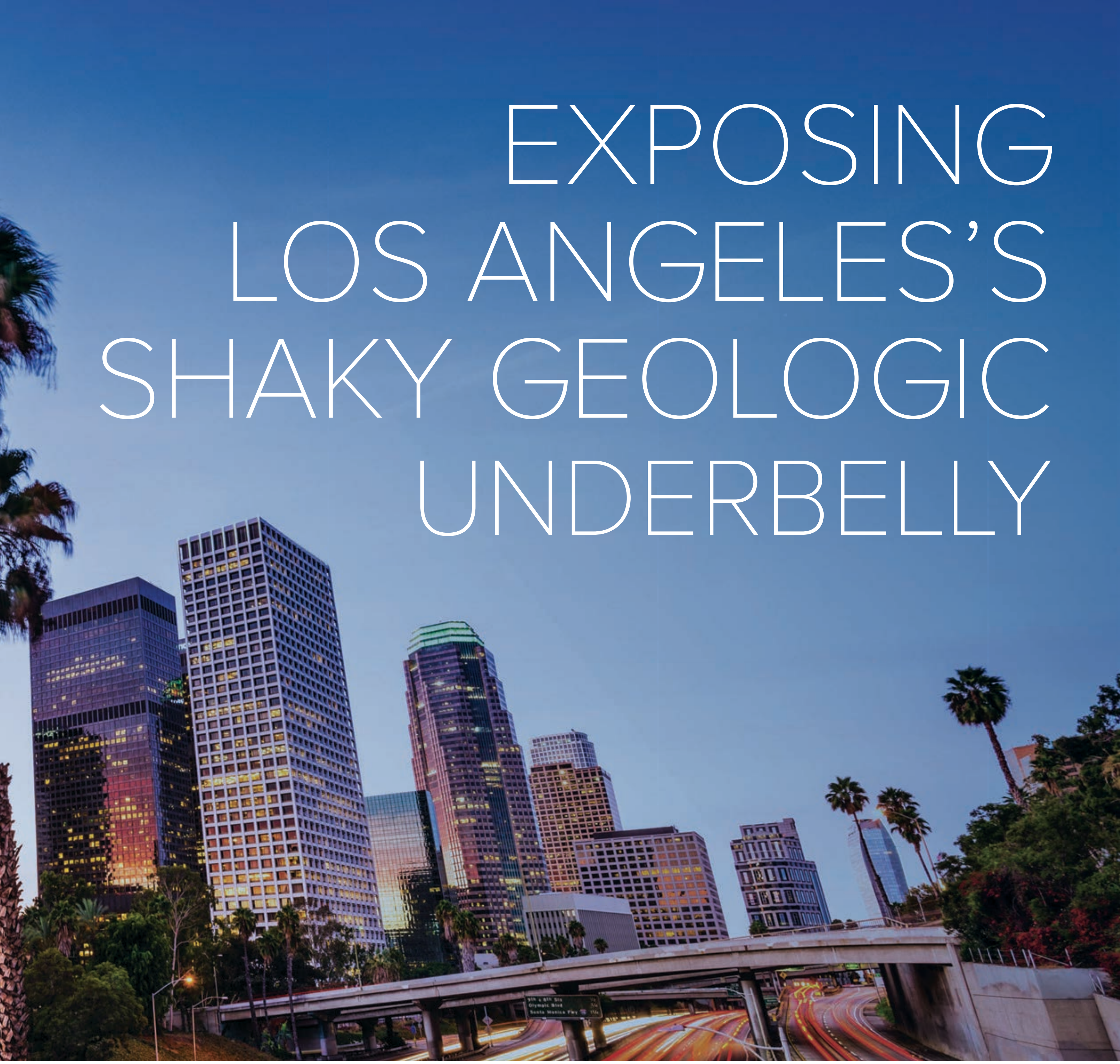
Current calculations might underestimate the susceptibility of Los Angeles to earthquake shaking, so researchers and volunteers are deploying seismic networks around the city to remedy a data shortage.

By Robert W. Clayton, Patricia Persaud, Marine Denolle, and Jascha Polet

EXPOSING LOS ANGELES'S SHAKY GEOLOGIC UNDERBELLY



Sean Pavone/Alamy Stock Photo

Los Angeles, Calif., is one of the 10 largest cities in the world that historically have been shaken by damaging earthquakes [*Bilham*, 2009]. The 1994 magnitude 6.7 Northridge earthquake, for example, sparked fires and collapsed roadways and buildings across the region. And although it caused no significant damage in Los Angeles, shaking from the Ridgecrest earthquake sequence that struck to the city's north last July served as a recent reminder of the city's seismic vulnerability. Little doubt remains whether a future large earthquake will strike this region: The question is only of when. Los Angeles therefore holds a special place in our existing understanding of—as well as in efforts to further illuminate—how best to mitigate natural hazards and their impacts on large populations.

The greater Los Angeles area—a megacity by the United Nations' definition—is the second-largest urban area in the United States, one of its fastest growing regions, and the third-largest city in the world based on combined statistical area. Here the seismic hazard is driven by the potential proximity of large earthquakes and complicated local structure. Sources of potentially damaging earthquakes in the Los Angeles area include the southern San Andreas Fault, located roughly 60 kilometers northeast of the city, as well as the series of faults that lie below the area and just offshore. Meanwhile, the col-

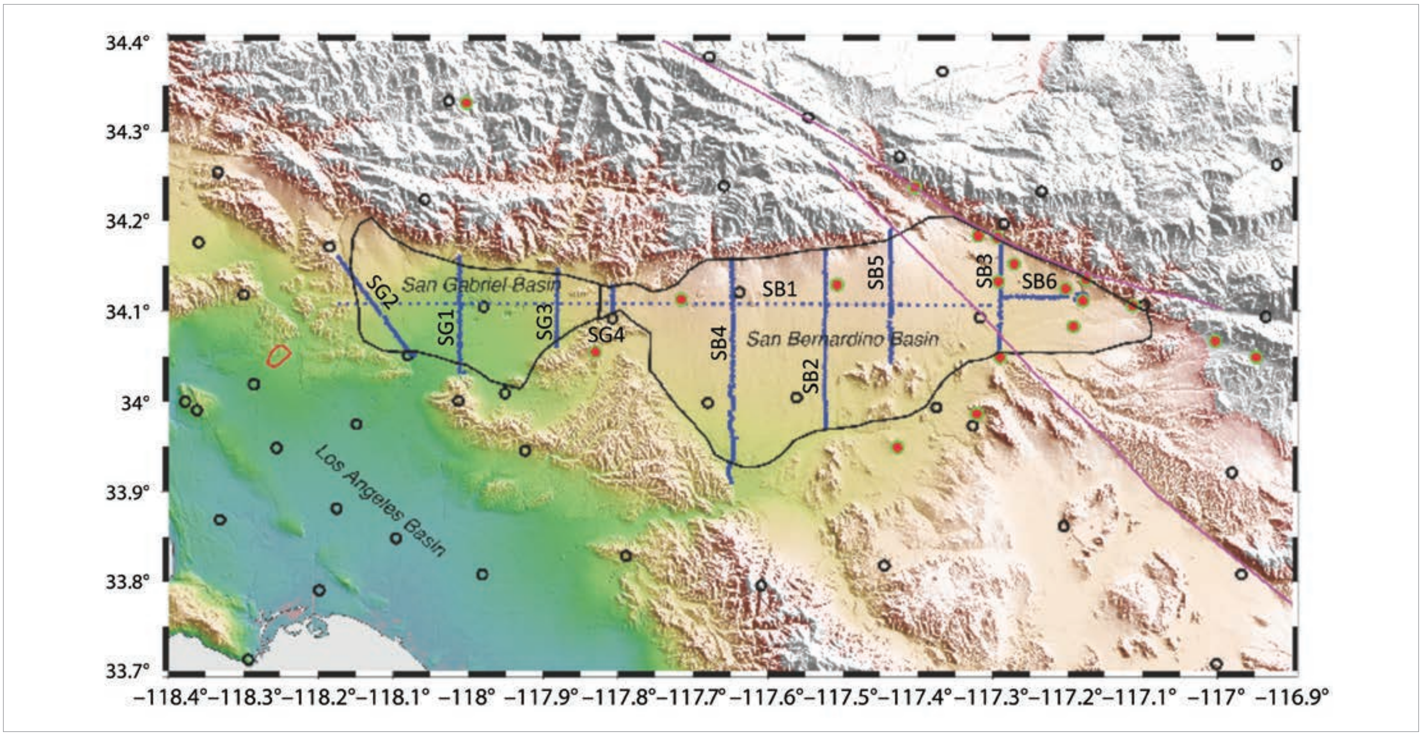


Fig. 1. The areas covered by the Basin Amplification Seismic Investigation (BASIN) surveys in the greater Los Angeles region are shown in this map. Sensor array lines are labeled SB for San Bernardino and SG for San Gabriel. Blue solid lines and blue dotted lines (now completed) comprise the 2017–2019 BASIN surveys. Open black circles are permanent seismic stations in the Southern California Seismic Network. Red dots are additional broadband stations temporarily deployed in 2018. The black outline marks the San Gabriel and San Bernardino Basins. Pink lines are the major faults in the area. The small red polygon shows the location of downtown Los Angeles.

lection of complex sedimentary basins underlying the area is known to amplify the motions from seismic waves [e.g., *Graves et al.*, 2011; *Lovely et al.*, 2006].

Through the ShakeOut scenario, CyberShake, and other similar efforts, scientists are working to improve estimates of the ground shaking that would result from a large earthquake in this region. A plausible event detailed in the original ShakeOut scenario [*Jones et al.*, 2008] is a magnitude 7–8 earthquake on the southern San Andreas Fault that causes large ground motions in downtown Los Angeles. One estimate of the ground motions in such a scenario, based on studying ambient noise correlations (correlations in background seismic signals) between seismic stations located on the San Andreas Fault and in downtown Los Angeles, suggests that these motions could be approximately 4 times larger than those predicted by current numerical simulations [*Denolle et al.*, 2014]. This indicates that our assessments of risk could underestimate the potential damage due to this type of earthquake.

The discrepancy between the different methods appears to stem from the fact that the northern basins in the Los Angeles area are not well characterized by the current 3-D seismic velocity models used in the computer simulations. Instead of allowing seismic energy to disperse into the surrounding region, the low seismic velocities and concave shapes of these basins—the San Gabriel (SG) and the San Bernardino (SB)—tend to trap energy and channel it toward the downtown Los Angeles area, which leads to larger ground motions [e.g., *Olsen et al.*, 2006].

Borehole and seismic reflection data in these basins are sparse, however, in part because oil companies—which have historically collected much of this sort of data—have not explored these basins as extensively as they have the Los Angeles Basin itself. This data shortage makes it difficult to determine precisely the shapes and seismic velocities of the basins, which hampers accurate earthquake hazard assessments. Additional data and improvements in the 3-D seismic velocity model used to simulate ground motions are thus of fundamental importance.

Volunteers Deploy Seismic Sensors

Starting in 2017, we set out to better determine the shapes and seismic velocities of the northern basins. We deployed dense 2-D seismic arrays across the San Gabriel and San Bernardino Basins (Figure 1), along with 20 additional seismic broadband instruments.

The data from these Basin Amplification Seismic Investigation (BASIN) surveys will be used to construct a 3-D model that should better predict the strong ground motions in downtown Los Angeles from events on the San Andreas Fault. These surveys are possible only because of a new type of seismic instrumentation—a compact, autonomous unit containing a standard 5-hertz three-component geophone, a battery, and a GPS clock—that was first used by oil companies in Los Angeles in 2011 [*Lin et al.*, 2013].

The BASIN surveys described here represent a new type of deployment that might be called “urban seismology.” The strategy we pursued involved installing instruments in linear arrays, with two-person teams deploying 16–20 stations each along portions of instrument lines. The teams were given maps marked with assigned points and were instructed to place a single instrument within a half-block radius of each point. They looked to site instruments at viable private residences or businesses or, if none were available, in median strips along roads or open fields. Whenever possible, sensors were completely buried in a 20-centimeter hole to minimize noise and to keep the instruments hidden.

The deployments involve considerable interaction with the public in seeking permission to place the sensors on private property. We generally have a high success rate if residents are at home and answer the door, and for this reason we usually deploy on weekends.

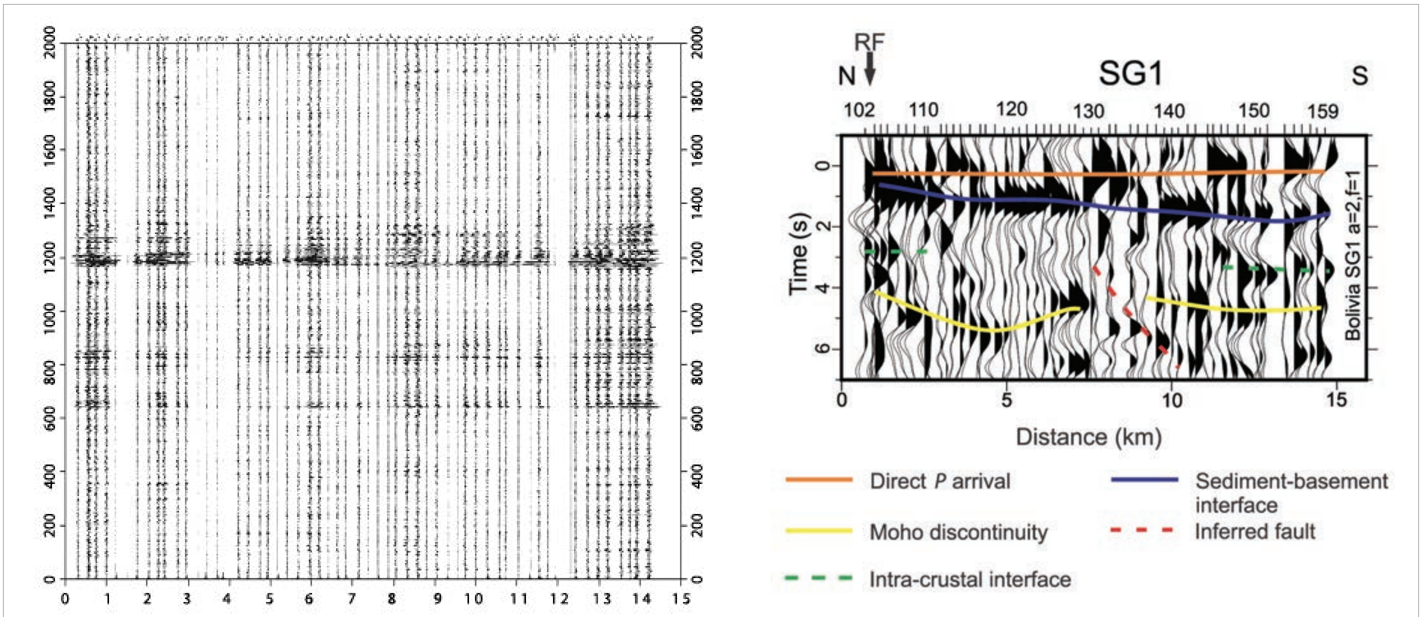


Fig. 2. Receiver functions, computed from three-component seismograms, show the relative response of Earth structure near a seismic sensor. The vertical component recordings at left were measured by sensors along the SG1 line of the BASIN surveys during a 2017 earthquake in Bolivia. The graph at right shows receiver functions (RF) computed from this earthquake as recorded along SG1, adapted from Liu et al. *[2018]. They reveal the 2-D structure beneath SG1, including the sediment–basement interface and the Moho, as well as a possible fault.*

Our deployment teams have included approximately 60 volunteers who span a diverse range of ethnicities, genders, and careers and range in age from high school students to retirees.

There is a certain level of risk that these instruments will be lost or damaged—to date we have lost 12 sensors, presumably because of theft. This is about 1% of the instruments we've deployed, which we consider an acceptable rate and inevitable with this type of survey. We also suspect that a couple of instruments were disturbed by coyotes.

We have completed all 10 planned sensor lines. These 10 lines comprise 732 sensor sites, which have generated some 6 terabytes of data at 250 samples per second. The average station spacing in the in-line direction is approximately 250 meters, and the stations remained operational for around 35 days on the basis of battery life.

> These surveys are possible only because of a new type of seismic instrumentation that was first used by oil companies in Los Angeles in 2011.

Structure from Data

We plan to use receiver functions—a technique to enhance seismic waves reflected off interfaces between layers in the subsurface—determined from moderate and large teleseismic earthquakes as far away as Fiji to determine the crustal structure beneath the sensor lines. Initially, we thought that the noisy environments of the basins would preclude effective recording of distant events, but this was not the case (Figure 2). The sensors along lines SG1, SG2, and SB4 clearly show the structure, including the Moho (the boundary between Earth's crust and mantle) and interfaces above this boundary [*Liu et al.*, 2018]. The sediment-basement interface (the bottom of the basins) is also well defined.

Determining a basin's effectiveness in channeling seismic energy is contingent upon determining the basin's shape and its shear wave velocity. To measure shear wave velocity, we plan to use the analysis of surface waves determined from ambient noise correlations, which has been shown to be effective in the Los Angeles region [*Lin et al.*, 2013].

Figure 3 shows an example in which Rayleigh and Love surface waves can be seen in the correlations. These types of waves have the largest amplitudes and thus produce the strongest ground motion. Also, Rayleigh and Love waves are most easily seen in correlations and thus are very useful for determining subsurface structure. We will do our initial analysis in a 2-D sense along the sensor lines and then extend the analysis to 3-D by including correlations between our instrument arrays and the instruments of the Southern California Seismic Network (SCSN), which has approximately 20 permanent stations within and surrounding the basins. We have determined that the correlations can be done over distances of up to 40 kilometers and for a frequency range (passband) from 1- to 10-second periods. During the deployment of our SB2, SB3, and SB6 lines, we also installed temporary broadband stations (shown in Figure 1) to supplement the SCSN stations.

We also plan to try a variety of other techniques to better determine the near-surface structure of the basins and the deeper structure beneath them, with the primary goal of producing better ground motion predictions for Los Angeles. These techniques include body wave tomography and full-waveform inversion using data from both earthquakes and correlations, horizontal-to-vertical spectral ratios, and autocorrelation imaging. We plan to incorporate the models we determine into the Southern California Earthquake Center's community velocity models. They plan to make the data available shortly.

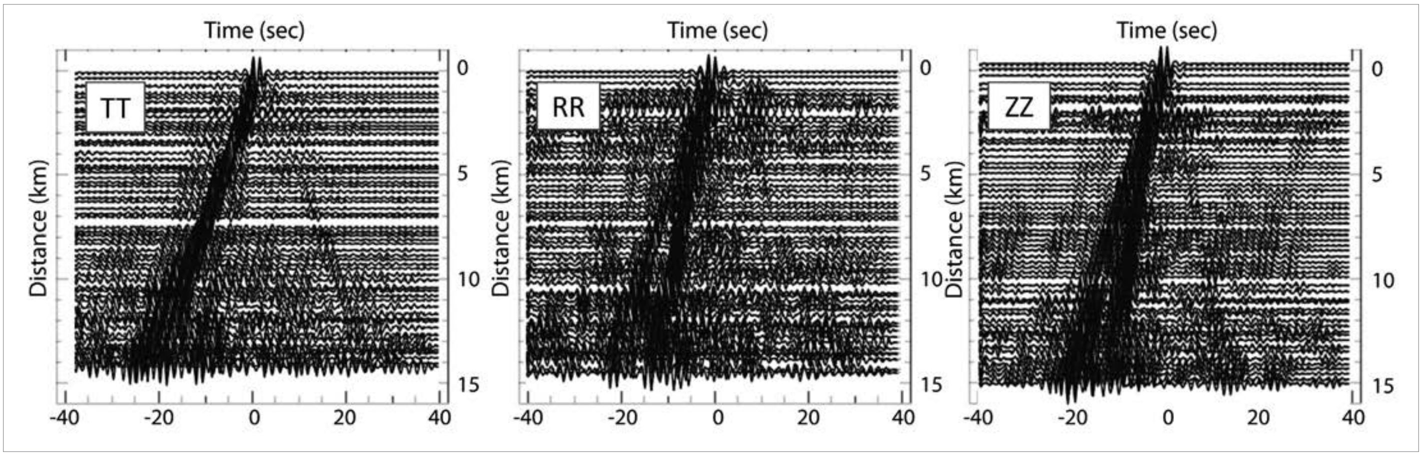


Fig. 3. These examples of ambient noise correlations show surface waves amplified by the structure of the San Gabriel Basin and detected along the SG1 sensor line. Distance on the vertical axis denotes distance along the line, and the horizontal axis represents the travel time of the wave to the sensors. The tangential-tangential (TT) correlations show Love waves traveling in both directions with respect to the sensor line. The radial (RR) and vertical (ZZ) graphs show the fundamental Rayleigh wave and its first overtone (a wave with twice the frequency of the fundamental wave).

Planning for Resilient Cities

Large earthquakes occurring close to vulnerable metropolitan areas present considerable risk, as demonstrated by the 2010 magnitude 7.0 earthquake in Haiti, which devastated the Port-au-Prince metropolitan area [*DesRoches et al.,* 2011]. In California alone, earthquakes cause average annual losses of about $3.7 billion, according to a 2017 report produced by the Federal Emergency Management Agency, the U.S. Geological Survey, and the Pacific Disaster Center. Losses from the next large earthquake in the state, if it affects a major urban area, are predicted to be even larger [*Branum et al.,* 2016].

Urban, high-seismic hazard settings such as Seattle, Vancouver, Dhaka, and Mexico City [*Pagani et al.,* 2018] that are also, like Los Angeles, underlain by sedimentary basins face additional hidden threats from the loose ground beneath them. In these cases, BASIN-type surveys are essential for obtaining realistic ground motions and accurately assessing seismic hazards and risks.

Urban growth will continue to be the largest contributor to global population increase for the foreseeable future. Thus, efforts to improve the resilience of cities, so that they are capable of withstanding large earthquakes, are an increasingly essential component of disaster mitigation and urban planning [*Godschalk,* 2003].

Efforts to improve the resilience of cities, so that they are capable of withstanding large earthquakes, are an increasingly essential component of disaster mitigation and urban planning.

Acknowledgments

We are grateful to the deployment and pickup crews from the California State Polytechnic University, Pomona; local California high schools; the Jet Propulsion Laboratory; the California Institute of Technology; and Louisiana State University who helped with the fieldwork; the Los Angeles area homeowners for their willingness to host the nodes; Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL), Louisiana State University, University of Utah, and University of Oklahoma for providing nodes; and the PASSCAL engineers for their help coordinating their nodes. P.P. thanks the Department of Geology and Geophysics at Louisiana State University for supporting this project. This research was partially supported by U.S. Geological Survey awards GS17AP00002 and G19AP00015 and Southern California Earthquake Center awards 18029 and 19033.

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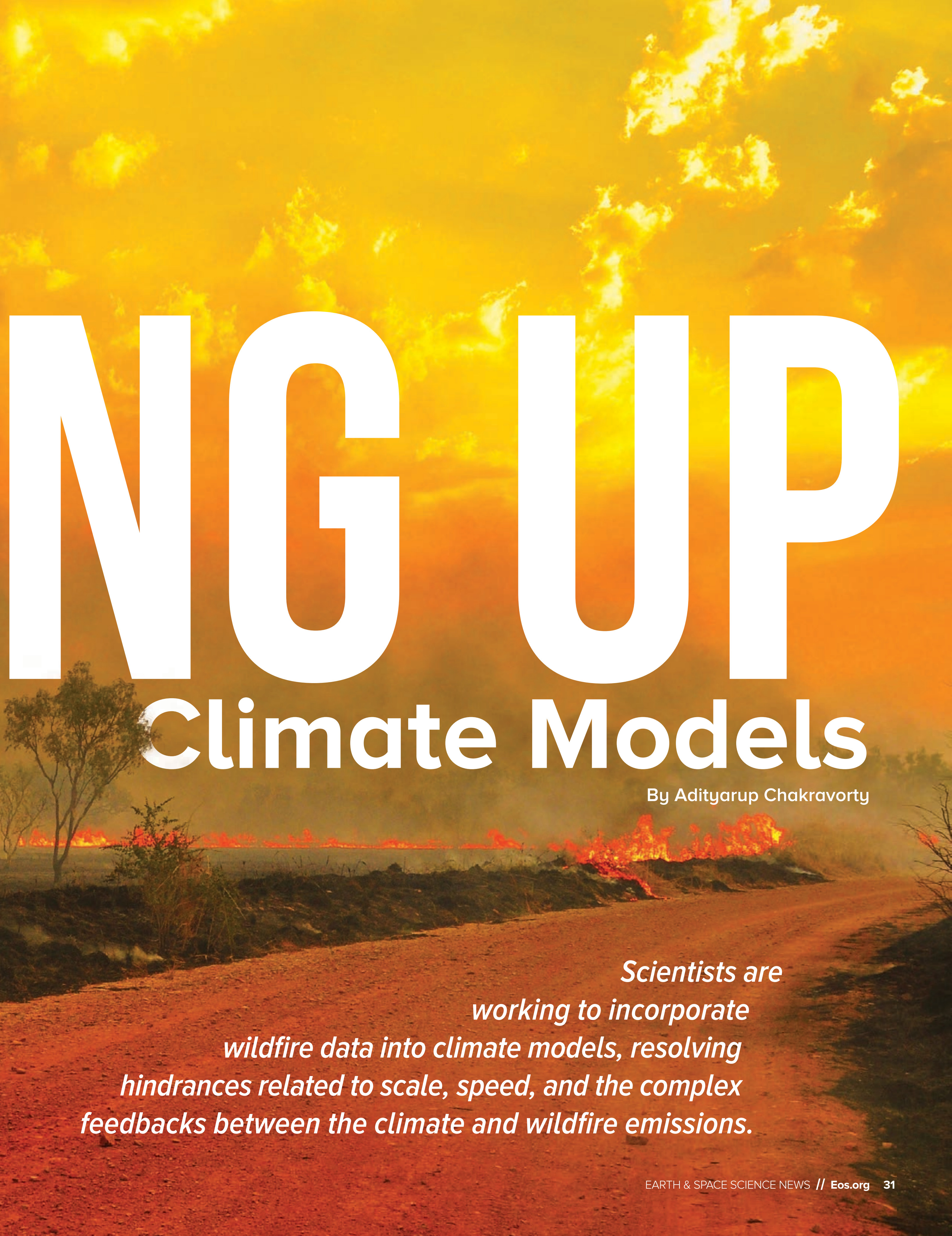
A wildfire burns in the Kimberley region of Western Australia.
Credit: John Crux Photography/Getty Images



NG UP Climate Models

By Adityarup Chakravorty

Scientists are working to incorporate wildfire data into climate models, resolving hindrances related to scale, speed, and the complex feedbacks between the climate and wildfire emissions.

IT'S August 2019, and Carsten Warneke is hunting for smoke. On board a NASA DC-8 aircraft packed with instruments, Warneke and other researchers have been locating and flying through smoke plumes from wildfires across the western United States for several weeks.

Warneke, an atmospheric chemist at the University of Colorado Boulder and the National Oceanic and Atmospheric Administration (NOAA), is part of the Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) project, a joint venture led by NOAA and NASA. A major goal of FIREX-AQ, according to the project's website, is to study "the chemistry and composition of smoke from wildfire and agricultural burning to improve weather, air quality, and climate forecasts." FIREX-AQ is just one of several research projects worldwide geared toward enhancing our understanding of how fires affect climate (and vice versa) and accurately incorporating fires and their smoky repercussions into regional and global climate models.

Earth is always burning. From 2003 to 2016, more than 13 million fires of various sizes and intensities flamed and smoldered across the planet. The United States alone has averaged nearly 67,000 fires annually in the past decade, with more than 46,000 fires occurring in 2019 as of late November. Worldwide, large expanses of Siberia have been aflame, with the fires sometimes covering areas the size of Massachusetts. In South America, tens of thousands of fires have blazed through the Amazon, the world's largest tropical rain forest, and thousands more have burned in the Pantanal, the world's largest tropical wetland. Bush fires rage across the Australian state of New South Wales, lowering air quality in nearby areas to unprecedented levels.

Wildfires can be anthropogenic, started accidentally or on purpose to clear forests for farming or animal husbandry, or to burn crop stubble on agricultural fields in preparation for a new planting season. Fires can also occur naturally—ignited by lightning strikes, for example.

Researchers agree that fires, whether large or small, human-made or natural, can significantly affect local, regional, and global climates in a variety of ways. Nonetheless, modeling the exact nature of these effects has been difficult. In fact, "most climate models currently do not include an interactive representation of wildfires, or, even if they do, the representation of such feedbacks has not been properly validated, given how recent a development this is," said Apostolos Voulgarakis, an atmospheric physicist at Imperial College London. There are several reasons fires and their emissions are difficult to incorporate into climate models, including differences in scale between fires and climate models; the speed with which fire emissions evolve once they enter the atmosphere; and feedbacks between fires and a changing climate.

"MOST CLIMATE MODELS CURRENTLY DO NOT INCLUDE A REPRESENTATION OF INTERACTIVE WILDFIRES, OR, **EVEN IF THEY DO, THIS IS DONE IN A SOMEWHAT UNSUCCESSFUL OR LIMITED WAY."**

Scaling: The Challenge

There are many drivers of global climate: Sunlight, cloud formations, and wildfire emissions all influence climate on local, regional, and global scales. These differences in scale matter tremendously because of how most modern global climate models are built.

In general, today's climate models divide Earth's surface into a 3-D grid. Each cell in this grid stretches north–south and east–west, and there are depths of atmosphere represented by multiple stacked cells. The models enforce fundamental laws of physics and use mathematical equations to represent processes taking place in Earth's oceans, land areas, atmosphere, and sea and land ice. They then calculate how various climate drivers force, or influence, these processes. The models simulate climate within each grid cell over a selected time step (usually minutes or hours) and calculate how each cell affects neighboring ones, ultimately cobbling together a snapshot of global climate. The whole process of these calculations is then repeated over multiple time steps until the desired overall timespan (years, decades, or centuries) is completed.

The size of grid cells determines the spatial resolution of a climate model. Smaller cells provide higher resolution but are much more computationally intensive and time-consuming. If each cell in a model represents 2° latitude × 2° longitude (roughly 200 × 200 kilometers at the surface near the equator), for example, and the model contains 20–40 vertical atmospheric layers, the model has to solve equations for almost half a million grid cells at each time step. And if the specified time step is half an hour, the model has to run calculations more than 1.7 million times for each grid cell to simulate global climate for 100 years.

So "when modeling global climate and wildfires at the same time, compromises need to be made," Voulgarakis said. "Certain processes cannot be represented adequately in existing climate model resolutions, with a prominent example being wind influences on wildfires."

Wind can heavily influence fire behavior, but on the grid scales of global climate models, "there is no hope of being able to represent small-scale wind patterns or terrain characteristics that influence the progression of fires," Voulgarakis said. (Global climate models skirt this issue by using a process called parameterization: averaging values, such as the height of surface features or the climate effects of cumulus clouds, over entire cells or using expected values based in part on past observations for these subcell-scale processes.)

Adam Kochanski, an atmospheric scientist at the University of Utah, noted that "the spatial scales of flames, where combustion actually occurs, are tiny compared [with] the scales relevant to climate problems," but also said that grid spacings used in regional climate models (versus global ones) "are approaching the resolutions needed to link fires with local climate capturing the fire-atmosphere feedbacks."

Kochanski is part of a National Science Foundation–funded project to develop the Multistage Wildfire Research and Prediction System (MWRPS), which aims to model fire-atmosphere interactions at a very small scale. "To successfully attack this problem, we will need a new class of reduced-complexity models that will be fast enough to be executed for large regions typically covered by climate models but at the same time [will] be able to render fire-atmosphere interactions," he said.

A Need for Speed

Another difficulty in adding fires into climate models is the speed with which fire emissions evolve in the atmosphere. In addition to ash, fires emit large amounts of reactive particles and gases (such as carbon dioxide, ozone, and methane) into the atmosphere, but "how these emissions affect air quality and climate depends on both what is emitted and how it evolves," said Emily Fischer, an atmospheric scientist at Colorado State University. "There are a lot of changes in the chemistry of smoke within the first few hours of its entry into the atmosphere." Without completely understanding how smoke chemistry changes over time, researchers cannot build accurate climate models that account for fire emissions.

Fischer is part of a National Science Foundation–funded program called the Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WE-CAN) project. The goal of WE-CAN is to "systematically characterize the emissions and first day of evolution of western U.S. wildfire [smoke] plumes," according to the project's website. In summer 2018, WE-CAN deployed a C-130 aircraft to sample fresh smoke from wildfires.

How chemicals in wildfire smoke evolve depends in part on atmospheric conditions like temperature and humidity. Those conditions can change with altitude and geographic location, so "the evolution of these [wildfire emissions] depends acutely on where they are injected into the atmosphere," Fischer and her colleagues wrote in a recent study (bit.ly/burning-emissions).

Most emissions are released close to the ground, but it's difficult for research aircraft to fly low over wildfires (and for ground-based teams to approach closely on foot). "We estimate that the earliest we sampled a smoke plume was 18–20 minutes after its formation," Fischer said. Sometimes, however, the plumes would be more than an hour old by the time measurements took place, long enough for the chemicals initially in the emissions to evolve into secondary compounds. Fortunately, Fischer and the WE-CAN team reached the plumes soon enough to be able to back-calculate levels and compositions of primary emissions based on the secondary compounds they detected.

Fischer and her colleagues are still analyzing the data collected by the WE-CAN flights, but they have already found some intriguing results. For example, "there is quite a lot of variability in the amount of reactive nitrogen species versus carbon compounds emitted even in the 20 or so fires we studied," she said. "We have compared these field data to lab measurements and [found that] burn conditions are driving

New projects and programs are working to better incorporate the effects of wildfires (like California's Camp Fire of 2018, above) into climate models. Credit: NASA some of the differences, but we don't understand all the reasons why." Although researchers are still exploring exactly how reactive nitrogen species affect climate, it is known that some of these compounds, such as nitrous oxide (N_2O), are strong greenhouse gases.

The Feedback Conundrum

One of the biggest challenges in incorporating fires into climate models is the two-way nature of the relationship between climate and wildfires. Fires affect climate, but weather and climate also influence fires. "For instance, fire smoke affects surface temperatures and winds that in turn impact the fire behavior itself, as well as smoke production and dispersion," Kochanski said.

Kochanski is part of a group of researchers who have coupled a widely used weather forecast model (the Weather Research and Forecasting (WRF) model) with a model called SFIRE which simulates how fire spreads. The result is WRF-SFIRE, a freely shared model that allows researchers to connect fires and atmospheric effects. It also allows linking of a chemistry module (WRF-SFIRE-CHEM), which adds simulations of emissions from fires based on fuel consumption rates and then models the chemical and physical changes of these emissions once they enter the atmosphere.

Feedbacks between fires and climate make it difficult to validate models, though. "Fire behavior and the local micrometeorology need to be sampled simultaneously to characterize all the processes shaping local weather and provide comprehensive data sets we can use to develop and validate models," Kochanski said. But that's easier said than done; an average forest fire can reach temperatures above 800°C (1,472°F). "As you can imagine, collecting such data in the wildfire environment is very difficult, and often impossible, due to safety concerns," Kochanski said.

But researchers are working on that: FIREX-AQ is one example of these attempts. In the summer and fall of 2019, the project (a collaboration between four federal agencies, more than 20 universities, and several private partners) used multiple aircraft, ground-based crews, and satellites simultaneously to gather information about smoke and emissions both from wildfires in the western United States and from prescribed agricultural fires in the southeastern United States. One aircraft focused on how emissions from fires changed with time, how these emissions evolved in the atmosphere, and how their distribution varied with altitude. A different aircraft collected meteorological data, including on the winds affected by the fire and how these winds in turn influenced emissions transport. "We are trying to look at fires holistically; that's the only way to get all the measurements you need to build robust climate models that incorporate fires," Warneke said.

Going Small for Big Understandings

Accurately measuring emissions from fires and understanding how they evolve in the atmosphere are big steps in building global climate models, but they're only part of the puzzle.

How primary emissions, and the secondary particles into which they evolve, affect atmospheric and climatic processes is another key piece. To understand these effects, Rajan Chakrabarty, an environmental and chemical engineer at Washington University in St. Louis, has gone to the microscopic level. "We study, for example, how the shape, mass, and optical properties of specific emissions change inside fires and then outside them," Chakrabarty said.

One type of fire emission that Chakrabarty has studied is black carbon, a particulate emission resulting from the incomplete combustion of carbonaceous materials like fossil fuels, agricultural leftovers, and other biomass. These tiny particulates strongly absorb sunlight, thus warming the atmosphere and changing cloud dynamics. Although they are relatively short-lived in the atmosphere, black carbon particles can still travel long distances through the atmosphere and be deposited in snowy or icy regions on land (such as in the Arctic or the Himalaya). In these regions, they can have myriad effects, including reducing the amount of sunlight reflected by snow and ice, and increasing melting, which in turn contribute to climate warming.

ONE OF THE BIGGEST CHALLENGES IN INCORPORATING FIRES INTO CLIMATE MODELS IS THE TWO-WAY NATURE OF THE RELATIONSHIP BETWEEN CLIMATE AND WILDFIRES. **FIRES AFFECT CLIMATE, BUT WEATHER AND CLIMATE ALSO INFLUENCE FIRES.**

Chakrabarty and colleagues were the first to discover that large, open fires, such as wildfires, emit a form of black carbon different from that seen in emissions from automobile exhaust or from domestic cooking or heating. Black carbon in wildfire emissions forms larger aggregates, called percolated aggregates, or PAs, that have significantly different optical properties and absorb more incoming solar radiation of certain wavelengths. "These observations suggest that soot PAs may have…previously unaccounted for impacts on climate forcing," according to Chakrabarty.

Whereas blazing forest fires emit large amounts of black carbon, smoldering fires, such as those seen when peatlands burn, emit different aerosols and particulates. Chakrabarty and colleagues have shown that peat fires emit mostly brown carbon and almost no black carbon. Unlike black carbon, which absorbs light across the visible spectrum, brown carbon absorbs near-ultraviolet and blue light, reflecting green, yellow, and red wavelengths.

"Initially, people thought that brown carbon particles would act like a mirror, because they reflect some light, and so offset the warming effects of black carbon in the atmosphere," Chakrabarty said. But his research has shown that brown carbon particles can absorb certain wavelengths of light that contribute to warming more strongly than black carbon particles. "So now we know [that] these particles can actually increase the net warming effects of black carbon."

Fires, from smoldering peat fires to blazing forest fires to the hazy burnings of farm stubble, are incredibly complex. Researchers are making progress in understanding the behaviors of different kinds of fires, the intricacies and evolution of their emissions, and the interactions of fires with the environment—all knowledge that is vital in improving the accuracy of climate models. There is a long way to go, however, and no time to waste as risks posed by wildfires to communities continue to grow and the climate continues to change. "We need to know these details [related to fires and emissions]," Warneke said, "to make accurate predictions of air quality and [to] model global climate."

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▶**Read the full story at bit.ly/Eos-wildfire-climate-models**

Celebrating the 2019 Class of Fellows

AGU president-elect Susan Lozier presented the newly elected class of Fellows at AGU's Fall Meeting 2019 Honors Ceremony, held 11 December in San Francisco, Calif. These individuals were recognized for their exceptional contributions to Earth and space science through a breakthrough, discovery, or innovation in their field. Please join us in congratulating our 62 colleagues who have joined the AGU College of Fellows!

A brief statement of the achievements for which each of the 62 Fellows was elected is provided below.

Zuheir Altamimi

For developing the International Terrestrial Reference Frame, the foundation for measuring motions of Earth's surface, sea level, and ice sheets.

Ronald Amundson

For pioneering the use of isotopes in the study of soils for interpreting land surface biogeochemistry and paleoclimate.

Jonathan L. Bamber

For pioneering satellite remote sensing in glaciology and building bridges to other disciplines of the geoscience community.

Barbara A. Bekins

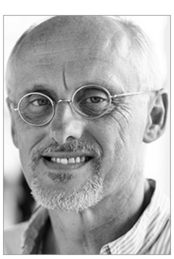
For groundbreaking contributions in subsurface contaminant hydrology, the effects of fluids on plate boundary faults, and induced earthquakes.

Jayne Belnap

For outstanding research in desert soil systems and their response to environmental and anthropogenic stresses.

Thomas S. Bianchi

For providing molecular-level detail and underlying mechanisms of the burial, transformation, and flux of carbon in dynamic coastal ecosystems.



Jean Braun

For his unselfish spirit and seminal contributions to our understanding of the complex coupling between Earth's topography, tectonics, and climate.

Ximing Cai

For forging a new science of hydrologic change accounting for human interaction and using it to advance water resources management.

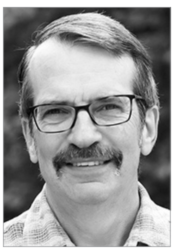
Ken Carslaw

For outstanding creativity in aerosol climate modeling.

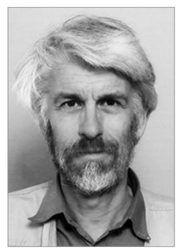
Benjamin Fong Chao
For outstanding contributions to the field of global geodesy with applications to hydrology, oceanography, and the dynamics of Earth's interior.

Patrick Cordier
For groundbreaking work using microscopy and simulation to understand mineral plasticity and its applications to seismology and geodynamics.

Rosanne D'Arrigo
For insightful, rigorous, and original contributions to the development of high-resolution paleoclimatology, particularly dendroclimatology.



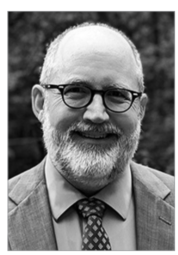
Eric A. Davidson
For advancing scientific understanding of soil nitrogen and carbon cycles that improves predictions of how they are altered by global environmental change.



Gert J. de Lange
For elegant contributions elucidating nonsteady state diagenetic processes that improve the interpretation of marine sedimentary records.

Andrew E. Dessler
For creative and incisive studies of the influences of water and clouds in the climate system.

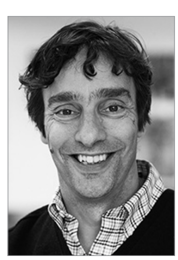
Michele K. Dougherty
For the study of outer planet systems.



Joseph R. Dwyer
For key contributions to understanding energetic radiation processes in our atmosphere and establishing the field of high-energy atmospheric physics.

James Farquhar
For innovations in isotope geochemistry that transformed our understanding of the evolution of Earth and life.

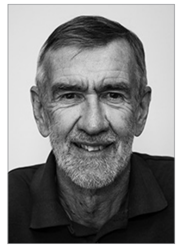
Mei-Ching Hannah Fok
For profound advancements in understanding the coupled geospace system during magnetic storms.



Piers Forster
For outstanding contributions to the development of knowledge on radiative forcing, Earth's energy balance, and climate sensitivity.

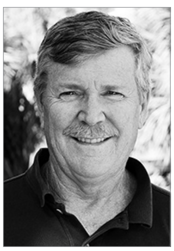
Christian France-Lanord
For developing and implementing geochemical tools to resolve tectonic controversies and to constrain rates of organic carbon burial and of erosion.

Antoinette B. Galvin
For exceptional contributions to our understanding of the properties of the solar wind, its solar sources, and its structure in the heliosphere.



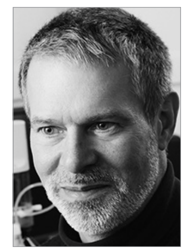
Peter R. Gent
For fundamental contributions to the understanding of the role of the ocean in the climate system and to its representation in Earth system models.

Taras Gerya
For fundamental contributions to our understanding of lithospheric and mantle dynamics from a planetary evolution perspective.



Dennis Arthur Hansell
For transformative insights into the biogeochemistry of marine dissolved organic matter and assessment of ocean carbon cycling.

Ruth A. Harris
For outstanding contributions to earthquake rupture dynamics, stress transfer, and triggering.



Robert M. Hazen
For impactful, sustained, and creative data science discoveries in mineral science and mineral evolution and for launching a new era to study Earth's history.

Kosuke Heki
For breakthrough discoveries and original research in geodetic science that have led to fundamental advances in our understanding of geodynamics.

Karen J. Heywood
For world-leading, innovative research on ocean physics, bottom water formation and export, and their impact on global climate.

Russell A. Howard
For fundamental contributions to understanding solar coronal mass ejections and remote sensing observations of the heliosphere.

Alan Jones
For fundamental studies of the solid Earth using electromagnetic methods and relating them to the broader Earth sciences.

Kurt O. Konhauser
For pioneering research at the intersection of biology and geology, giving us vital new ways to ponder Earth's past relationships with life.

Sonia M. Kreidenweis
For elucidating aerosols' role in climate and visibility by quantifying their hygroscopic growth and cloud condensation/ice nuclei activity.

Kitack Lee

For transformational discoveries of the impacts of anthropogenic carbon and nitrogen inputs to the ocean.

Zheng-Xiang Li

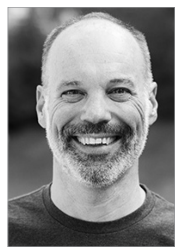
For insights into restoring pre-Pangean supercontinents and their connections to mantle superswells, true polar wander, and snowball Earth.

Jean Lynch-Stieglitz

For developing new methods for reconstructing past ocean circulation and for advancing understanding of the late Quaternary deepwater and climate variability.

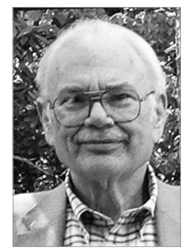
Kuo-Fong Ma

For fundamental advances in earthquake source physics using geophysical and geological data.



Reed Maxwell

For outstanding contributions toward the advancement of integrated hydrological simulation across scales.

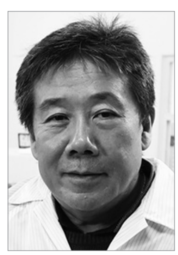


John W. Meriwether

For fundamental contributions to understanding the thermal and dynamical structures in Earth's upper atmosphere.

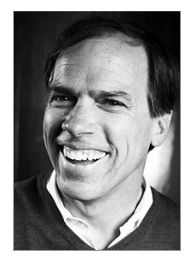
Son Van Nghiem

For remote sensing innovations leading to breakthroughs in Earth science research and applications to hazard mitigation ranging from fire to ice.



Yaoling Niu

For stimulating a new understanding of the relationships between mantle evolution and melt generation at oceanic plate boundaries.



Thomas Howell Painter

For breakthrough contributions to the understanding of snow-related runoff generation processes and their measure in mountainous environments.

Beth L. Parker

For fundamental advancement in characterizing contaminant mobility in fractured sedimentary rocks.

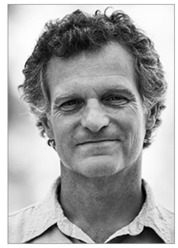
Ann Pearson

For pioneering and transformative contributions concerning the origins and paleoceanographic significance of microbial biomarkers.

Graham Pearson

For sustained contributions on the age, origin, and evolution of the continental upper mantle.

Lorenzo Polvani
For fundamental contributions to the understanding of the dynamics of tropospheric–stratospheric interactions and their role in climate change.



Peter W. Reiners
For validating the U-Th/He thermochronology technique and using it creatively to solve key geological problems.

Yair Rosenthal
For fundamental contributions to the development of deep-ocean paleothermometry and understanding of Pleistocene and Cenozoic climate changes.

Osvaldo Sala
For integrative research on biodiversity and ecosystem functioning with sustained impact to science and society.

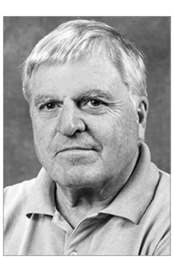
Edward "Ted" Schuur
For being a global leader in research that has fundamentally contributed to understanding the vulnerability of permafrost carbon to climate change.

Sybil Putnam Seitzinger
For fundamental research on the human impacts on the biogeochemistry of the Earth system and for inspiring policy solutions.

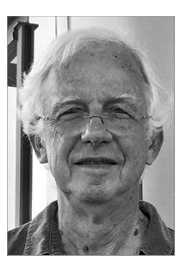
Toshihiko Shimamoto
For outstanding contributions to fault and earthquake mechanics, in particular to mechanics of faulting at seismic slip rates.

Adam Showman
For groundbreaking work on the dynamics of planetary atmospheres, inside and outside the solar system, and the geophysics of icy satellites.

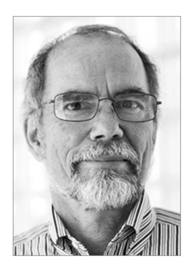
Alex Sobolev
For groundbreaking work on magmatic melt inclusions and phenocrysts to unravel the nature and source of compositions of mantle-derived melts.



Carl I. Steefel
For pioneering and cross-disciplinary work on fluid–rock systems through innovative reactive transport model development and application.



John Suppe
For seminal contributions in structural geology and tectonics, including fold–fault kinematics and thrust belt and strike-slip fault mechanics.



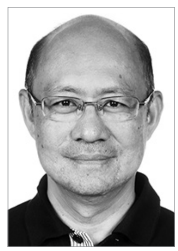
Karl E. Taylor
For improving our ability to evaluate and intercompare climate models and for advancing understanding of climate forcings, responses, and feedbacks.

Meenakshi Wadhwa
For outstanding contributions to the understanding of solar system chronology and the chemistry of Mars.

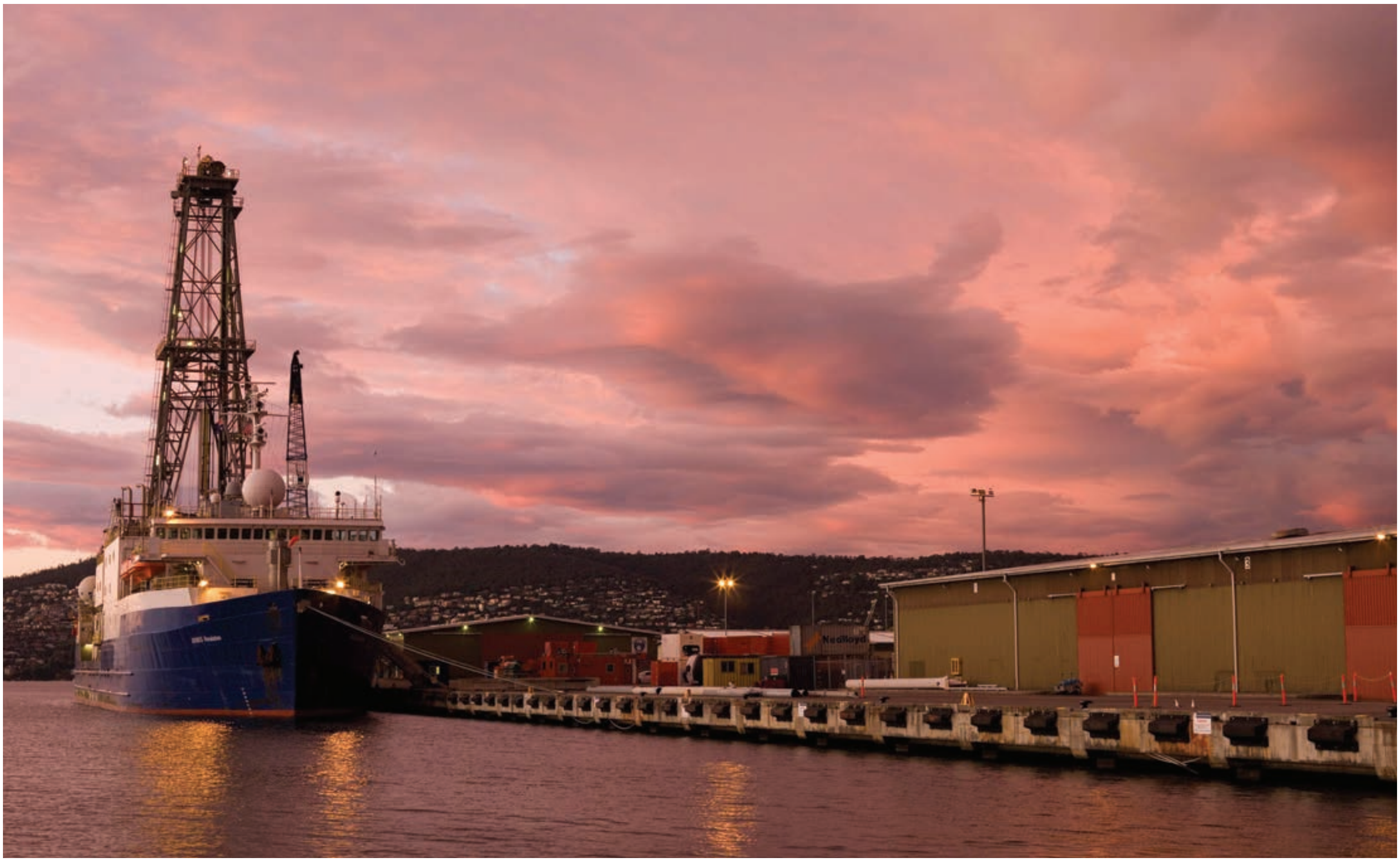
Michael J. Walter
For advances in understanding the formation of Earth and its core, the petrology of the mantle, and the phase relationships of the deep Earth.

John S. Wettlaufer
For fundamental contributions to understanding the physics of ice from molecular to geophysical, climatic, and planetary scales.

Chunmiao Zheng
For elucidating solute transport mechanisms in heterogeneous porous media and developing codes for analysis of groundwater solute transport.



Tong Zhu
For exceptional contributions to advancing fundamental atmospheric chemistry and to assessing impacts of megacity air pollution on human health and climate.



A compilation of seismic and stratigraphic data from across the Australian–Antarctic Basin is providing new constraints on paleoceanographic circulation in the basin. Here the International Ocean Discovery Program's (IODP) JOIDES Resolution *sits in port in Hobart, Tas., Australia, following IODP Expedition 318 in 2010, during which sediment drill cores analyzed in the new research were collected off the Antarctic coast. Credit: John Beck, IODP,* JOIDES Resolution *Science Operator, CC BY 4.0 (bit.ly/ccby4-0)*

An Integrated History of the Australian–Antarctic Basin

Understanding the nature of sedimentary rock deposits in the Australian-Antarctic Basin is crucial for learning how oceanographic conditions evolved as Earth transitioned from a warm and humid Late Cretaceous "greenhouse" to a cool and dry Cenozoic "icehouse" world. Yet unraveling the tectonic, climatic, and oceanographic history of this basin, which began rifting in the Middle to Late Jurassic roughly 165 million years ago, has been challenging because of a paucity of data as well as varying interpretations of each margin.

Sauermilch et al. have, for the first time, collated all available data to construct a unified seismostratigraphic framework for the Australian-Antarctic Basin. The team's extensive data set includes more than 500 seismic reflection lines collected across the region, some of which have only recently become available through the Scientific Committee on Antarctic Research, as well as newly obtained data about marine sedimentary rocks from offshore drilling efforts.

The compilation indicates that prior to the start of Antarctic glaciation about 34 million years ago, both margins of the basin experienced similar patterns of sedimentation and thus share three key sedimentary units that are similar in both thickness and structure. They include a unit deposited between the Late Cretaceous and mid-Paleocene (about 94 million–58 million years ago), when sedimentation along both margins was dominated by large river systems that formed offshore delta deposits up to 5 kilometers thick in the still-narrow ocean basin.

Later in the sedimentary record, the presence of drift deposits along both continental rises indicates that by about 58 million years ago in the late Paleocene, ocean bottom currents had begun circulating clockwise within the widening basin. The authors suggest that these currents then grew stronger and progressed eastward through the Eocene (56 million–34 million years ago) while global cooling and increasing aridity led to a large reduction in the amount of sediment shed from both continents. These conditions ultimately led to a dearth of sediment deposition in the basin during the middle to late Eocene, as demonstrated by two large-scale hiatuses found in International Ocean Discovery Program cores from the Antarctic continental slope.

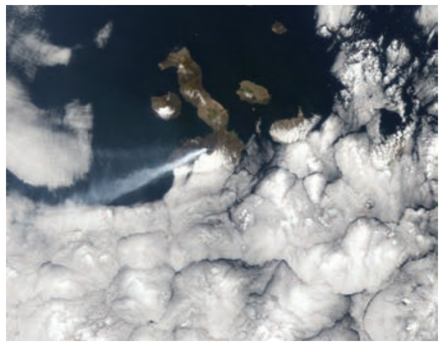
The integrated seismostratigraphic model developed in this study offers new insights into the history of the Australian-Antarctic Basin, providing new constraints on landscape evolution and ocean circulation that should be incorporated into future paleoceanographic models of the basin. (*Journal of Geophysical Research: Solid Earth,* https://doi.org/10.1029/2018JB016683, 2019) **—Terri Cook,** *Science Writer*

Forecasting Volcanic Eruptions with Artificial Intelligence

Most of the roughly 1,400 active volcanoes around the world, including many in the United States, do not have on-site observatories. Lacking ground-level data, scientists are turning to satellites to keep tabs on volcanoes from space. Now, using artificial intelligence, scientists have created a satellite-based method of detecting warning signs of when a volcano is likely to erupt.

Gaddes et al. took advantage of satellites that carry instruments equipped to collect imagery using interferometric synthetic aperture radar (InSAR), which can detect centimeter-scale deformations of Earth's surface. Every time one of the satellites passes over a given volcano—typically once every 12 days—it can capture an InSAR image of the volcano, from which ground movement away from or toward the satellite can be calculated.

InSAR often can pick up the ominous expansion of the ground that occurs when magma moves within a volcano's plumbing, but it is difficult to continuously monitor the huge number of images produced by the latest generation of SAR-equipped satellites. In addition, some volcanoes exhibit long-lasting deformation that poses no immediate threat,



Ash from Sierra Negra, a volcano on Isla Isabela in the Galápagos Islands, drifts across the sky during an October 2005 eruption. Researchers used satellite data leading up to a 2018 eruption at Sierra Negra to test an algorithm designed to detect signals that indicate potential volcanic unrest. Credit: NASA image created by Jesse Allen, Earth Observatory, using data obtained courtesy of the MODIS Rapid Response Team

and new images must be compared with older ones to determine whether a deformation at a volcano is a warning sign or just business as usual.

To solve these issues, the researchers turned to machine learning, a form of artificial intelligence that can glean subtle patterns in vast quantities of data. They developed an algorithm that can rapidly analyze InSAR data, compare current deformation to past activity, and automatically create an alert when a volcano's unrest may be cause for concern.

To test the algorithm's viability, the team applied it to real data from the period leading up to the 2018 eruption of Sierra Negra, a volcano in the Galápagos Islands. The algorithm worked, flagging an increase in the ground's inflation that began about a year before the eruption. Had the method been available at the time, the team writes, it would have accurately alerted researchers that Sierra Negra was likely to erupt. (*Journal of Geophysical Research: Solid Earth,* https://doi.org/10.1029/2019JB017519, 2019) **—Emily Underwood,** *Science Writer*

Sunlight Stimulates Brown Algae to Release Organic Carbon

The many sources and fates of dissolved organic carbon in the ocean interest scientists because of the numerous important roles this material plays in marine ecosystems and in Earth's carbon cycle. In new research, *Powers et al.* suggest that brown algae, such as kelp and other types of seaweed, might be a key source of dissolved organic compounds called polyphenols.

Previous research has shown that macroscopic brown algae produce a class of polyphenols known as phlorotannins, an important part of algal cell walls, during their normal biological activities. However, the relative importance of brown algae as a source of marine polyphenols and other forms of dissolved organic carbon has been unclear.

Sargassum natans, *a seaweed commonly found in the Gulf of Mexico, releases large amounts of carbon compounds known as polyphenols into the ocean. Credit: James St. John, CC BY 2.0 (bit.ly/ccby2-0)*

Researchers studied brown algae known as *Sargassum natans,* which is commonly found in the Gulf of Mexico, the western Atlantic Ocean, and the Sargasso Sea. They conducted experiments with the algae under natural and artificial sunlight, monitoring how much and which types of dissolved organic carbon they released.

The scientists found that *S. natans* releases large amounts of dissolved organic carbon in response to natural sunlight, which might help protect it against damage from ultraviolet irradiation. Accounting for the estimated biomass of *S. natans* in nature, the findings suggest that the species is a major contributor of dissolved organic carbon in the Gulf of Mexico and the western North Atlantic.

In the experiments, polyphenols made up about 5%–18% of the compounds released by the algae, making *S. natans* the biggest biological source of open-ocean polyphenols currently on record. Further research is needed to clarify what happens to these polyphenols after they are released, but the researchers noted that the findings challenge earlier conclusions that all polyphenols found in the ocean originate from land-based life. (*Global Biogeochemical Cycles,* https://doi.org/10.1029/2019GB006225, 2019) **—Sarah Stanley,** *Science Writer*

Curiosity Rover Reveals Oxygen Mystery in Martian Atmosphere

The Martian atmosphere is thin and cold and consists mostly of carbon dioxide. Although certainly unsuitable for humans, Martian air could hold clues to whether other life-forms live—or once lived—on the Red Planet. *Trainer et al.* report the first measurements of the five major components of the Martian atmosphere captured over several seasonal cycles.

The researchers made the new measurements over almost 3 Martian years (about 5 Earth years) using the Sample Analysis at Mars (SAM) instrument suite on NASA's Curiosity rover. In that time, Curiosity explored a 16-kilometer stretch of Gale Crater, located near the equator. Four or five times per season (like Earth, Mars has a winter, spring, summer, and fall), SAM collected an air sample to examine the atmosphere's composition.

On average, the data revealed, the equatorial Martian atmosphere consists of 95% carbon dioxide, 2.59% nitrogen, 1.94% argon, 0.161% oxygen, and 0.058% carbon monoxide. However, throughout the year, some of these concentrations vary widely because of seasonal freezing of carbon dioxide at the planet's poles, which periodically removes much of this gas from the atmosphere.

With its suite of scientific instruments, the car-sized Curiosity rover can sample both the surface and the atmosphere of Mars, helping search for signs of past and present habitability. Credit: NASA/JPL-Caltech/MSSS

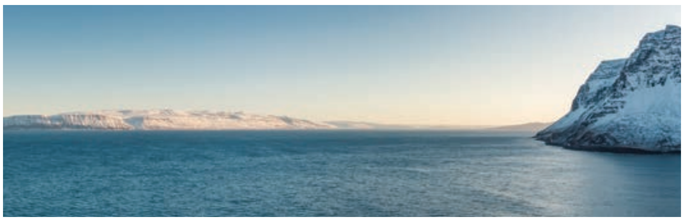
Seasonal polar freezing—and subsequent thawing—of carbon dioxide also causes atmospheric pressure to rise and fall throughout the year. SAM measurements showed that nitrogen and argon concentrations at the equator reflect these seasonal pressure changes, but with a time delay. This result suggests that seasonal pressure changes drive movement of air across the planet faster than the gases in the air can mix to reflect each season's composition.

The researchers also found unexpected patterns in seasonal and year-to-year oxygen concentrations that cannot be explained by any known atmospheric or surface processes on Mars. They suggest that these variations could be due to chemical reactions in surface rocks but note that further research is needed to solve this mystery.

The new findings provide a clearer picture of seasonal atmospheric compositions on Mars, which could aid in the ongoing search for signs of past or present life on the planet. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2019JE006175, 2019)

—**Sarah Stanley,** *Science Writer*

Theoretical Models Advance Knowledge of Ocean Circulation



In the North Atlantic Ocean (e.g., near Iceland, seen here), warm and salty water from the tropics cools and sinks before flowing back toward the Southern Hemisphere, a process known as the Atlantic Meridional Overturning Circulation (AMOC). In recent decades, theoretical modeling has revealed a wealth of knowledge about the dynamic processes that drive the AMOC. Credit: Arctic-Images/The Image Bank/Getty Images Plus/Getty Images

In the northern reaches of the Atlantic Ocean, warm, salty waters delivered from the tropics by prevailing winds cool and sink before flowing back toward the Southern Hemisphere. This process, known as the Atlantic Meridional Overturning Circulation (AMOC), transports heat and nutrients and plays a key role in Earth's climate system.

Decades of research have deepened scientists' understanding of the AMOC and its importance. Now a study by *Johnson et al.* synthesizes recent advancements in modeling the fundamental processes that drive and maintain this powerful circulation system.

The new review focuses on theoretical models that deal with pared-down conceptual perspectives on the AMOC, rather than on more complex attempts at realistic simulations. The authors discuss progress in modeling the many large- and small-scale factors that influence the AMOC, from Southern Hemisphere wind patterns and intermediate-sized eddies to the shape of continents and the bathymetry of ocean basins.

Recent theoretical models have also explored variability and anomalies in the AMOC, not just its average patterns. Some have explored why the AMOC exists in the first place, instead of a Pacific meridional circulation system. And other theoretical studies have aided interpretation of real-world observations, such as those made by the ongoing Rapid Climate Change–Meridional Overturning Circulation and Heat-flux Array project, which uses an array of sensors to continuously measure AMOC dynamics at 26.5°N latitude.

In addition to compiling recent advancements, the study addresses what is on the horizon for continuing research in this field. For instance, theoretical approaches may help researchers interpret measurements from ongoing observational projects, such as the Overturning in the Subpolar North Atlantic Program (OSNAP), and may generate hypotheses that could be tested using the newly collected data.

The authors emphasize the critical role of theoretical modeling in understanding the AMOC and in linking that understanding to ocean and climate models, which could improve understanding of how the AMOC influences and is influenced by climate change. (*Journal of Geophysical Research: Oceans,* https://doi.org/10.1029/2019JC015330, 2019) **—Sarah Stanley,** *Science Writer*

A "Super" Solution for Modeling Clouds

Accurately representing clouds and convection in weather and climate models is one of the thornier challenges facing climate modelers. Cloud droplets form on micrometer scales, whereas convective updrafts and downdrafts, which play vital roles in cloud formation, can extend over distances of up to 10 kilometers.

Current global climate models operate with resolutions of 10–100 kilometers and thus cannot resolve these processes directly. Instead, cloud processes are represented with numeric approximations known as parameterizations. For example, climate models depict the transport of heat and moisture in a cloud using values that describe the rate and direction of movement of heat and moisture in the atmosphere. However, these approximations gloss over the dynamic, small-scale processes that drive cloud formation in reality, so the resulting representations of clouds in these parameterizations contain significant uncertainty.

This uncertainty with respect to clouds is the main source of uncertainty in model-based projections of future global warming; more clouds in a future climate will dampen global warming, whereas fewer clouds will amplify the warming. Furthermore, uncertainty in cloud representations also contributes to systematic errors in simulated precipitation patterns.

In a recent study, *Jansson et al.* demonstrate a new approach to modeling clouds. The authors used a method known as superparameterization, in which individual parameterizations are replaced by a smaller-scale and more accurate simulation of cloud processes in a global circulation model. Superparamaterizations have been applied before in global climate models, but new in this study is the use of three-dimensional, high-resolution large eddy simulations as the cloud-resolving model. The new technique also allows users to restrict the superparameterization to a given geographic area to control computational costs.

The authors implemented their procedure using the Dutch Atmospheric Large Eddy Simulation and the Open Integrated Forecast System (OpenIFS) and demonstrated the superparameterized setup by simulating conditions on an April day in 2012 over part of the Netherlands.

The model more accurately reproduced cloud top height measurements observed by the Moderate Resolution Imaging Spectroradiometer aboard the Terra satellite compared with the standard parameterized version of OpenIFS. The superparameterized model also showed improvements in representing specific humidity.

The results of the study indicate that superparameterization using large eddy simulations could improve the representation of clouds in global circulation models. Furthermore, the work provides a foundation for developing future parameterization approaches and the use of different local models.

However, the authors note that future work is needed to validate the approach fully and that there is room for improvement. For instance, the geographic area over which the superparameterized model can be applied is limited by computational constraints, and the model did not capture cloud structure well. Nevertheless, the demonstration cleared a significant technical hurdle and shows promise for future climate modeling efforts. (*Journal of Advances in Modeling Earth Systems* (*JAMES*), https://doi.org/10.1029/2018MS001600, 2019) **—Aaron Sidder,** *Science Writer*

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Review of applications will begin immediately with a deadline of 18 February 2020.

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Tenure-track Faculty Position in Tectonic Petrochronology. The Department of Geosciences at the University of Arizona seeks to hire a tenure-track Assistant Professor in petrochronology—an emerging field that explores the power of minerals to serve as time capsules that yield information about pressure, temperature, deformation, and interaction with fluids during their evolution. The appointee is expected to develop a high-profile, externally funded research program, teach undergraduate- and graduate-level courses in solid-Earth aspects of geology, and contribute to departmental, university, and external service. The position is open to applicants who hold or are about to graduate with a Ph.D. The Department of Geosciences seeks faculty who promote diversity in research, education, and outreach, and who have interests in collaborative research and curricular activities.

This position has excellent opportunities for collaboration given existing strengths in igneous petrology/geochemistry, U-Th-Pb geochronology (Arizona LaserChron Center), noble gas geochemistry/geochronology (Arizona Noble Gas Laboratory), TIMS-based geochronology and petrogenesis, and fission-track geo/thermochronology, and in using this information to address problems in tectonics, sedimentary geology, landscape evolution, paleoclimate, and planetary science. The successful candidate will be encouraged to utilize existing infrastructure in geochemistry and geochronology within the Department of Geosciences, which includes a Hitachi SEM (with EDS, EBSD, and color CL capabilities), an ELA-SC-ICPMS (Element2), an ELA-MC-ICPMS (Nu Plasma), two new noble gas mass spectrometers (Helix MC and Argus VI), and two ID-TIMS mass spectrometers. Additional instrumentation is available from the Kuiper Materials Imaging and Characterization Facility, including two SEMs (one equipped with Raman), FIB-SEM, TEM, and two EMPA instruments.

The Department of Geosciences at the University of Arizona features perennial top-ten ranked programs in geology, geophysics, and geochemistry, and a growing emphasis in climate science and paleoclimatology. The University of Arizona also has top planetary science, hydrology, and engineering departments with significant potential for collaboration.

Review of applications will begin January 6, 2020 and will continue until position is filled. Required application materials include: a (1) curriculum vitae; (2) statement of research interests and accomplishments; (3) statement of teaching interests and qualifications; (4) vision statement describing how the candidate would develop their research program, (5) statement describing the candidate's experience in working with diverse students, diversifying a department, or demonstrating success in increasing a sense of academic inclusiveness; and (6) list of at least three references (including mail and email addresses and telephone numbers) to: <https://uacareers.com/postings/43205>. Equal Opportunity Employer Minorities/Women/Vets/Disabled.

Assistant/Associate Geochronologist and Director of the Nevada Isotope Geochronology Laboratory. The Department of Geoscience at the University of Nevada Las Vegas invites applications for a full-time, tenure-track/tenured faculty position in 40Ar/39Ar geochronology, other radiogenic geochronologic systems, or related fields at the Assistant or Associate Professor level. The successful candidate will serve as the director of the Nevada Isotope Geochronology Laboratory (NIGL). NIGL has a dedicated state-funded lab manager that runs day-to-day operations, holds a MAP 215-50 mass spectrometer with furnace and CO_2 laser sources, and is housed in a state-of-the-art LEED certified building dedicated to analytical instrumentation, and which will have a complete multi-collector ICP-MS facility for other radiogenic systems. We are particularly interested in individuals who integrate geochronological investigations with innovative geochemical or other analytical techniques in the pursuit of interdisciplinary research. Opportunities for collaboration exist with departmental groups focused on research in Solid Earth, Paleoclimatology, Surficial Processes and Planets. In addition to NIGL, the department hosts facilities that include electron microprobe, SEM, LA-ICP-MS, and upcoming MC-ICP-MS instruments as well as stable isotope, fluid inclusion, imaging, mineral separation, cryptotephra, and medical geology labs. The successful candidate is expected to establish (Assistant-level), or expand upon (Associate-level) a vigorous, externally funded research program; direct and grow NIGL at UNLV; teach effectively at both undergraduate and graduate levels; and perform service duties at all levels. The Geoscience Department (https://geoscience.unlv.edu) has 21 faculty, ~240 undergraduate students, and ~50 MS/PhD students. UNLV is a Carnegie top research status institution, ranks among the nation's most diverse campuses, and has graduate programs rated among the nation's top 100, including Geoscience. This position requires a Ph.D. from a regionally accredited college or university in Geoscience or a related discipline. Applicants seeking appointments at the Associate Professor level with tenure must have a significant record of transformative funded research and publications in support of the rank and must be able to meet UNLV tenure requirements. Salary is competitive with those at similarly situated institutions. Position is contingent upon funding. The successful applicant could begin as early as Fall, 2020.

Application materials must include a cover letter, curriculum vitae, proposed research plans (three page limit), statement of teaching philosophy and interests (two page limit), a statement of past or potential contributions to diversity (one page limit), and contact information for five referees. Although this position will remain open until filled, review of candidates' materials will begin on January 9, 2020 and best consideration will be gained for materials submitted prior to that date. The successful candidate will demonstrate support for diversity, equity and inclusiveness as well as participate in maintaining a respectful, positive work environment. UNLV is an EEO/AA/Vet/Disability Employer. Materials should be addressed to Dr. Wanda Taylor, Geochronology Search Committee Chair, and submitted at https://www.unlv.edu/jobs. For assistance with the application process, please contact UNLV Human Resources at (702) 895-3504 or applicant.inquiry@unlv.edu

Ocean Sciences

Assistant or Associate Professor of Ocean Engineering. The Division of Marine Science (DMS) in the School of Ocean Science and Engineering (SOSE) at The University of Southern

University of Dayton

LECTURER IN GEOLOGY,
SPECIALIZING IN GEOGRAPHIC INFORMATION SYSTEMS
Starting August 16, 2020

The Department of Geology invites applications for a twelve month, annually renewable, non-tenure-track lecturer position. This is a full time and benefit-eligible position. The successful candidate will be expected to teach four courses per semester during the regular academic year. These courses include Geographic Information Systems (GIS) and introductory geography or geology. As part of the teaching load, the candidate is also expected to mentor students in GIS-related capstone projects. Summer duties include: teaching GIS classes, capstone projects and geology field camp as needed, and supporting geospatial initiatives across campus such as the Hanley Sustainability Institute and the Human Rights Center.

Minimum qualifications:

· A Ph.D. in geography, geology, environmental geoscience, or a closely related field is required at time by **June 30, 2020**

· Must be able to teach introductory and advanced GIS courses using the ESRI GIS software, and to mentor in GIS-related capstone projects.

· Must possess effective written communication skills

Application process:

For a complete list of qualifications and to apply, go to:
http://employment.udayton.edu/cw/en-us/job/497660/lecturer-in-geology-specializing-in-geographic-information-systems

Mississippi (USM) invites qualified applicants for a full-time, 9-month, tenure-track faculty position in Ocean Engineering at the assistant or associate professor level to begin in Fall 2020. The successful candidate will be expected to contribute to the continued development of the undergraduate Ocean Engineering program, which started in 2017, and lead its ABET accreditation. Moreover, the candidate is expected to develop a strong, externally funded research program, publish in peer-reviewed literature, mentor students, participate in undergraduate instruction and develop courses in their area of study. The candidate should demonstrate the potential to contribute across disciplines and promote the continued interdisciplinary growth of the academic and research programs within the SOSE. Applicants must hold a Ph.D. in engineering or a related field and have demonstrated research experience related to the ocean. The preferred candidate has post-doctoral research experience, has participated in an ABET accreditation process, has experience in managing an established research group, and has a demonstrated record of scholarship, service, grant development, communication, and commitment to diversity. The successful candidate will be required to pass a NASA background security check and a USM employment background check.

Applications must be submitted through the jobs.usm.edu candidate portal: https://usm.csod.com/ats/careersite/JobDetails.aspx?id=1247. For questions regarding this position, contact the chair of the search committee by email: maarten.buijsman@usm.edu.

The SOSE includes two academic divisions, Marine Science, and Coastal Sciences, and several R&D centers including: Hydrographic Science Research Center, Marine Research Center, and Thad Cochran Marine Aquaculture Center. DMS is based at the NASA Stennis Space Center, which is a 'federal city' that boasts the world's largest concentration of oceanographers and hydrographers. 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, and the National Centers for Environmental Information.

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 undergraduate 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 near the Port of Gulfport, which is the home port for USM's R/V Point Sur and the recently opened USM Marine Research Center, which features a state-of-the-art fabrication lab, testing tank, and laboratory space. Gulfport will be the future home port of a new 199-ft UNOLS Regional Class Research Vessel, which will be managed by a USM-lead consortium.

USM is an Affirmative Action/Equal Employment Opportunity employer/Americans with Disabilities Act institution.

Planetary Sciences

Director/Department Head – Lunar & Planetary Laboratory/Planetary Sciences. Since its founding in 1960, the Lunar and Planetary Laboratory (LPL) at the University of Arizona (UArizona) has been at the forefront of planetary science and solar systems research. LPL currently leads some of NASA's highest-profile missions and instruments and is continuously seeking future opportunities. LPL is engaged in a broad range of research that includes theoretical, experimental, and observational investigations of our solar system, as well as exoplanets and their origins. LPL integrates spacecraft missions and cutting-edge analytical facilities into its research portfolio, and its teaching and graduate program produces scholars who become leaders in the field. More information about LPL and the Department of Planetary Sciences is available from lpl.arizona.edu. LPL is searching for a new Director/Department Head. The successful candidate will have demonstrated excellence in planetary science research, strong leadership and management skills, teaching experience, and a commitment to diversity. The Director is expected to lead LPL in developing and executing a clear vision during a period of expansion. The LPL Director works with local and external stakeholders such as NASA and NSF to maintain and grow an enriching environment conducive to excellence in planetary science research, education, and exploration. For full position description and to apply online, please see https://www.lpl.arizona.edu/director-department-head. The University of Arizona is an EEO/AA employer–M/W/D/V.

ETH*zürich*

Professor of Engineering Geology

→ The Department of Earth Sciences (www.erdw.ethz.ch) at ETH Zurich invites applications for a tenured full professorship in Engineering Geology.

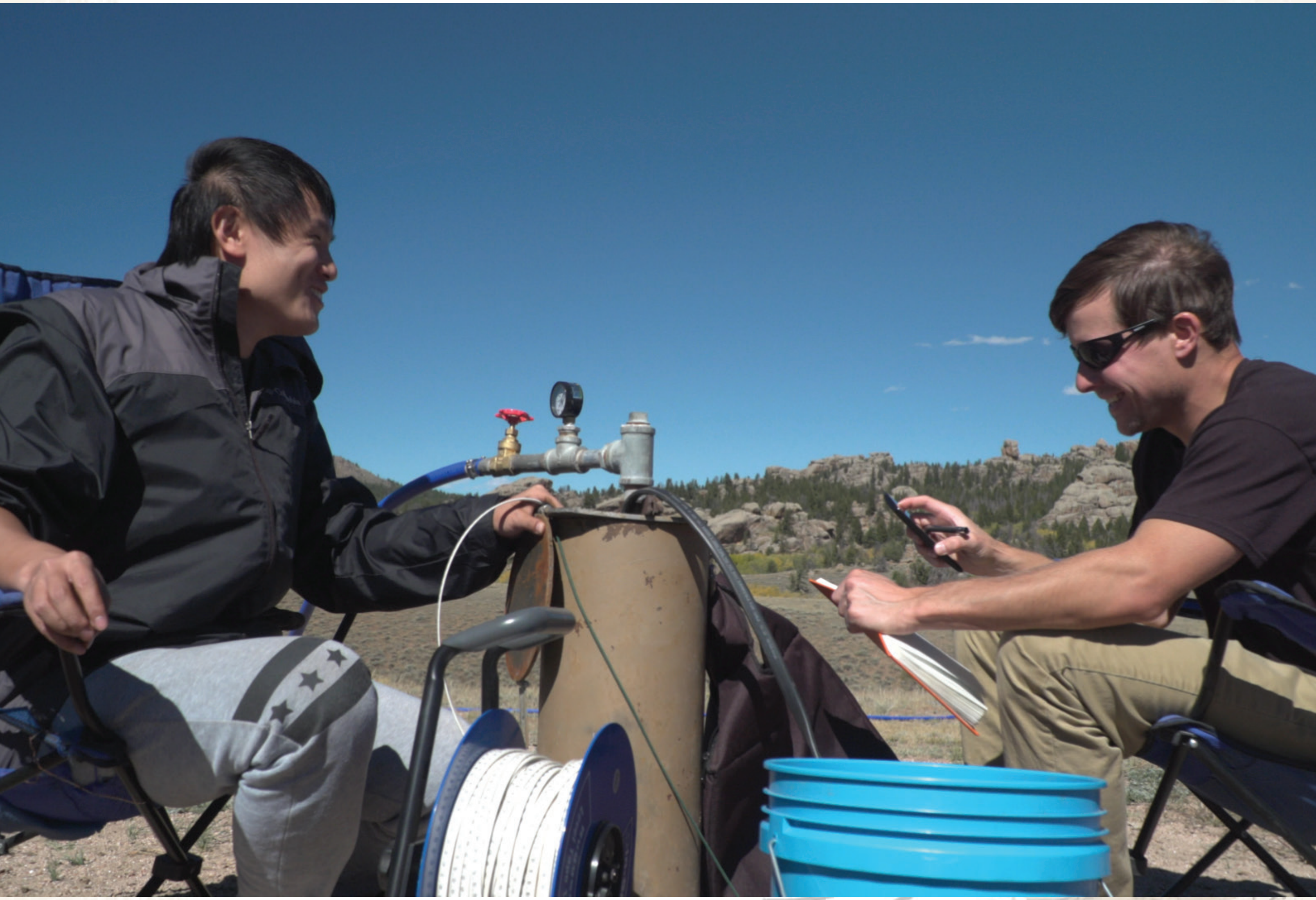
→ The successful candidate is expected to create and oversee an innovative research programme directed at topics closely related to engineering geology, including the construction of engineered structures (tunnels, bridges, dams, landfills, nuclear repositories), development of near-surface resources (groundwater, geothermal energy, carbon sequestration and mineral deposits) and the assessment and mitigation of geohazards and georisks. The successful candidate will combine an array of approaches, including field measurements, in-situ laboratories, remote sensing technology and numerical simulations at scales ranging from the laboratory to the large field scale. A strong analytical background is expected. She or he is a leading scientist with a proven record of innovative research, and the ability to connect with companies and government agencies dealing with Engineering Geology topics of high societal relevance.

→ The new professor and her/his research group will be expected to contribute to introductory and advanced courses in engineering geology, and to teach relevant field and laboratory methods. In general, at ETH Zurich undergraduate level courses are taught in German or English and graduate level courses are taught in English. The professor also leads the Certificate in Advanced Studies (CAS) in applied Earth Science. She or he should be an internationally visible personality with a network and experience in the field of engineering geology. In addition to profound professional qualifications and competence, leadership competence is a prerequisite.

→ The Department of Earth Sciences at ETH Zurich is actively striving to increase the number of women professors in order to build a more diverse intellectual community.

→ **Please apply online: www.facultyaffairs.ethz.ch**

→ Applications should include a curriculum vitae, a list of publications, a statement of future research and teaching interests, and a description of the three most important achievements. The letter of application should be addressed **to the President of ETH Zurich, Prof. Dr. Joël Mesot. The closing date for applications is 15 March 2020.** ETH Zurich is an equal opportunity and family friendly employer, and is responsive to the needs of dual career couples.



Dear AGU:

Hello from the Blair Wallis Fractured Rock Research Well Field in the beautiful Laramie Range in southeastern Wyoming. Since 2015, we have been drilling, instrumenting, and testing bedrock wells completed in fractured granite at Blair Wallis, which lies in a headwater mountain watershed with a hydrology dominated by snowmelt. The photo depicts students Shuangpo Ren (left) and Sam Coker checking the water level in well BW-7 before starting a 44-hour constant-rate pumping test.

In the background are outcrops of the same bedrock granite. As can be seen from the outcrops, and verified by our hydraulic testing of the wells, the bedrock is extensively fractured in the subsurface, providing permeable pathways for snowmelt recharge and groundwater flow. We hope that our research at Blair Wallis will shed light on bedrock flow processes in this mountain range and on how downstream aquifers are replenished by mountain outflows.

Read more at bit.ly/hydrological-connectivity.

—**Ye Zhang**, University of Wyoming, Laramie

View more postcards at bit.ly/Eos-postcard